

LAWRENCE LIVERMORE NATIONAL LABORATORY

REACHING THE THRESHOLD OF IGNITION

AN IN-DEPTH LOOK AT NIF'S 1.35-MEGAJOULE MILESTONE



Managing Editor
Benny Evangelista

Writers
Charlie Osolin, Jon Kawamoto,
Benny Evangelista, Allan Chen,
and Michael Padilla

Art Director
James Wickboldt

Copy Editor
Margaret Davis

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REACHING THE THRESHOLD OF IGNITION

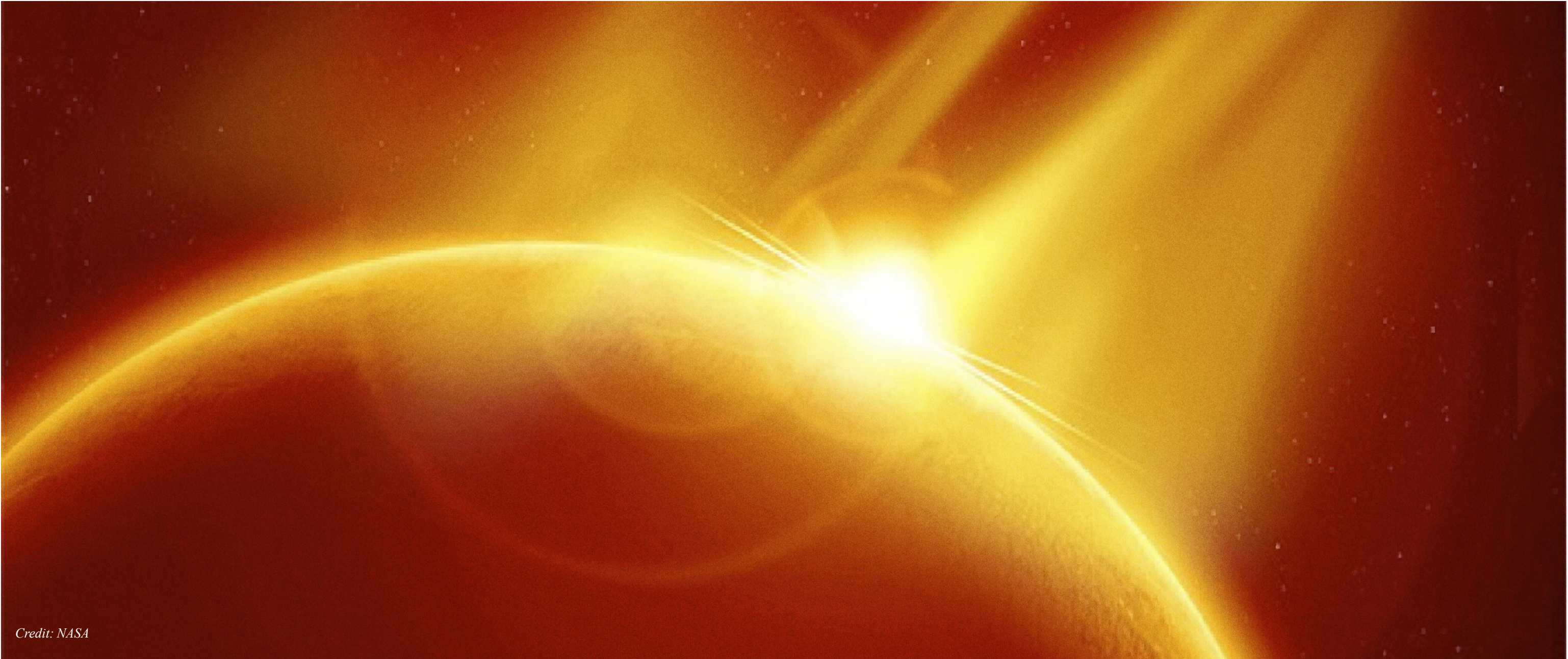
An In-Depth Look at NIF’s 1.35-Megajoule Milestone

Foreword by Kim Budil, LLNL Director



On Aug. 8, 2021, researchers at Lawrence Livermore National Laboratory (LLNL)’s National Ignition Facility (NIF) achieved a historic milestone with an experiment that produced a fusion energy yield of 1.35 megajoules (MJ).
The experiment was the result of advances and insights developed over the last several years by a Lab-wide team building on a foundation of decades of research and development by an enormous range of partners, collaborators, and stakeholders. The result opens the door to exciting new NIF applications in support of stockpile stewardship

by enabling us to study robustly burning plasmas for the first time since underground testing ended. The success also creates new opportunities to get to much higher fusion yields on NIF and is a critical step toward realizing the potential of inertial fusion energy. It truly is the first step into a very bright future and a moment of enormous pride for the entire community.
The following articles describing aspects of NIF’s record-breaking experiment were originally posted as a series of stories on the NIF & Photon Science Directorate’s website, lasers.llnl.gov.



Chapter 1

BUILDING TO A SOLUTION:

The Elements of a Fusion Breakthrough

If it takes a village to raise a child, it takes an international community of scientists, engineers, technicians, and many other contributors to create an inertial confinement fusion (ICF) experiment capable of producing more than 1.3 million joules of fusion energy.

The record-setting Aug. 8, 2021, experiment on the National Ignition Facility (NIF), the world’s largest and highest-energy laser system, was the culmination of years of research and development in lasers, optics,

diagnostics, target fabrication, experimental design, and computer modeling and simulation.

Those advances have brought researchers to the threshold of ignition, as defined by the National Academy of Science and the National Nuclear Security Administration (NNSA), in which a NIF implosion produces more fusion energy than the amount of laser energy delivered to the target. This result enables access to a new experimental regime for

the field of high energy density (HED) science and the science-based Stockpile Stewardship Program.

By firing its 192 high-energy lasers into a fusion target the size of a pencil eraser, NIF is able to produce temperatures of more than 100 million degrees Kelvin and pressures of hundreds of billions of Earth atmospheres—conditions found only in the center of massive stars and in exploding nuclear weapons.

The record shot was the latest in a series of progressively higher-energy-yield experiments on NIF, each building on earlier successful experiments with a variety of previously demonstrated tactics, advances in target fabrication and laser technology, and new understanding driven by data from past experiments and increasingly sophisticated measurement and simulation technology.

The remarkable 1.35-megajoule (MJ) breakthrough was enabled by contributions from every facet of Lawrence Livermore National Laboratory (LLNL)’s NIF & Photon Science and Weapons and Complex Integration (WCI) teams, colleagues throughout LLNL, and partners in the worldwide fusion, plasma, and HED science communities.

“An incredible amount of teamwork got us to this point,” said former NIF Director Mark Herrmann, now program director for WCI’s Weapon Physics and Design Program, “from conceiving of inertial confinement fusion 60 years ago in the revolutionary work by (former LLNL Director) John Nuckolls to developing a series of lasers, advancing the optics, advancements in target fabrication, advances in computer simulations, advancing

the designs, understanding the science, and fielding the diagnostics that allow us to measure these extraordinary events.”

Many of these advances were supported by funding from Laboratory Directed Research and Development (LDRD) programs at LLNL and other NNSA labs.

Among the key improvements:

- Innovative experimental designs increased the size of the target capsule, reduced the aperture of the laser entrance holes, and extended the duration of the laser pulse, achieving record levels of energy coupled to the hot spot at the center of the target capsule.

- Terabytes of data from NIF’s suite of dozens of state-of-the-art nuclear, x-ray, and optical diagnostics dissected every aspect of the more than 170 ignition experiments conducted since 2011, making NIF implosions

among the best-diagnosed HED experiments in the world. Those data were analyzed to provide insights and build understanding of previous ICF implosions and to enhance the predictive ability of computer models. Data from past experiments also helped researchers understand and overcome obstacles to improving implosion performance.

- Enhanced experiment-based modeling and simulation helped shape the new experimental designs. Computer codes were used to design, optimize, construct, and field experiments while continually advancing understanding of key multi-physics mechanisms. The Aug. 8 shot also benefited from a simplified data-based model to guide design choices.

- Advancements in the metrology and fabrication of custom-made targets culminated in the deployment of the highest-quality high-density carbon (diamond) target, in terms of surface and internal defects and unwanted contamination, yet used on NIF.

- Improvements in the fidelity of laser models, accuracy of the laser diagnostic, beam quality, and symmetry, coupled with increasingly robust optics, enabled the laser to operate at its highest sustained level of energy and power to date, helping boost the pressure and temperature in the hot spot.

The 1.35-megajoule result built on nearly a decade of advances by LLNL researchers and their collaborators, under the leadership of ICF Program Director John Edwards, Deputy Associate Program Director for ICF Science Richard Town, ICF Chief Scientist Omar Hurricane, ICF Program Associate Division Leader Debbie Callahan, and Chief Experimentalist Nino Landen, along with many others. They guided the team to address and gradually solve a wide range of challenges that had limited NIF’s implosion performance. Edwards and his team worked in lockstep with a NIF leadership team that included Herrmann, NIF Chief Engineer (now NIF Director) Doug Larson, Target Fabrication Program Manager Abbas

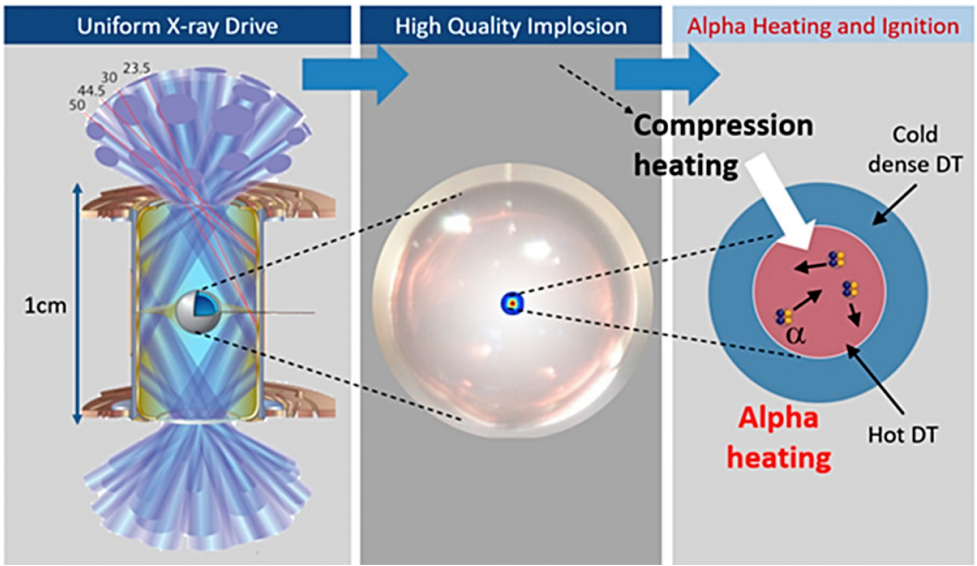


Illustration of alpha heating in a standard NIF target.

Nikroo, and NIF Operations Manager Bruno Van Wonerghem.

“All of this work was only possible because of the efforts and accomplishments of the amazing teams that designed and built NIF

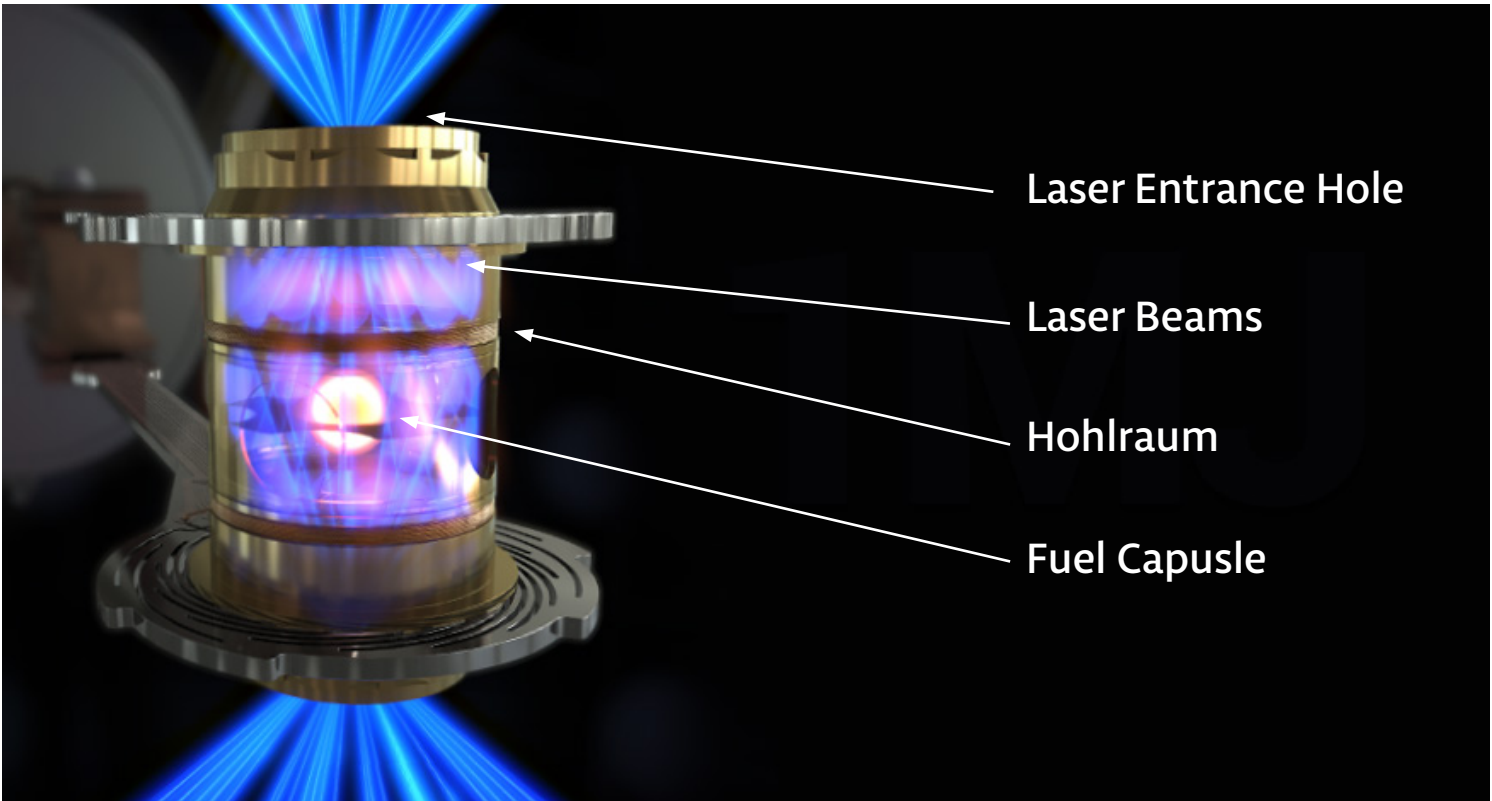
NIF ignition experiments began in 2011 as part of NNSA’s National Ignition Campaign (NIC), which ended Sept. 30, 2012. The campaign had two principal goals: developing a platform for ignition and HED science appli-

cations (including target and diagnostic fabrication) and transitioning NIF to routine operations as the world’s preeminent HED science user facility.

Over the course of the campaign, NIF researchers steadily increased the laser’s energy and power, culminating on July 5, 2012, when the laser

system’s 192 beams delivered more than 1.8 megajoules of ultraviolet light and more than 500 trillion watts of power to the center of the Target Chamber.

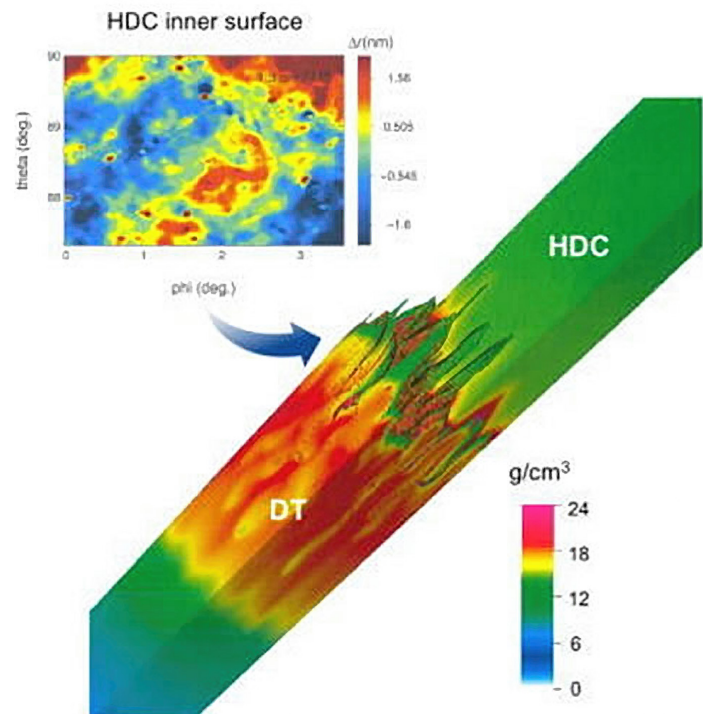
2011–2012: NIC experiments produced fusion yields of only a few kilojoules, far less than computer models predicted. The implosions were unstable and asymmetrical, with a high level of energy-sapping laser–plasma interactions (LPI). Although ignition was not achieved, a large body of scientific knowledge and major new experimental, diagnostic, modeling, and target fabrication capabilities were developed and validated, helping guide subsequent experiments.



Schematic of a NIF ignition target. The fuel capsule is suspended inside a gold or other high-Z (high atomic number) cylinder, the hohlraum. The laser beams enter the target at the ends of the cylinder through laser entrance holes and strike the inside of the hohlraum to generate x rays, which ablate the surface of the capsule and cause a rocket-like, high-velocity implosion. The extreme pressures and temperatures cause deuterium and tritium atoms in the capsule to fuse, releasing enormous amounts of energy. Credit: Jake Long

For example, researchers found that slightly tweaking the wavelength of certain laser beams could control the exchange of energy between the beams as they entered the laser entrance holes, an effect known as cross-beam energy transfer (CBET), which had been a major cause of asymmetry. Key diagnostics, such as the Velocity Interferometer System for Any Reflector (VISAR), the streaked X-ray Spectrometer (NXS), and the Dilation X-ray Imager (DIXI), capable of acquiring 200 billion images a second, were fielded to capture every detail of NIF implosions, with many more state-of-the-art diagnostics to follow.

2013–2015: With the introduction of the “high-foot” design—which increased the power in the first stage, or foot, of the laser pulse and shortened the pulse duration—stability was improved and the mixing of capsule material with the fusion fuel was reduced, but at the cost of lower compression. Still, the high-foot implosions were the first



A high-resolution 3-D simulation of a 2017 NIF shot at the time of peak implosion velocity showing the effects of capsule surface roughness. Significant mixing between the high-density carbon (HDC) ablator, or target capsule, and deuterium-tritium (DT) fuel has occurred by this time, including long fingers of hot HDC that have penetrated halfway through the DT.

to demonstrate significant alpha heating, where the energy generated through fusion reactions exceeded the amount of energy deposited in the fusion fuel and hot spot by the implosion, a condition known as fuel gain.

In alpha heating, alpha particles (helium nuclei) produced in the target capsule’s central hot spot deposit their energy in the cold deuterium-tritium (DT) fuel surrounding the hot spot, heating the fuel, increasing the rate of fusion reactions, and producing more alpha particles. This bootstrapping process is the mechanism required to accelerate the DT-fusion burn rate to eventual self-sustaining fusion burn, known as burning plasma, and ignition. The high-foot experiments achieved about 25 kilojoules of yield, double the yield that would have resulted without alpha heating.

2016–2018: “Exploding pusher” experiments using high-density carbon (HDC), or diamond, capsules had shown the possibility of reducing LPI using hohlraums with low gas fill. Researchers began to use HDC capsules instead of the plastic capsules previously used; HDC and “Bigfoot” experiments with these capsules reduced LPI, improved symmetry, increased implosion velocity, and more than doubled the energy yield to about 55 kilojoules.

The Target Fabrication team worked to shrink the size of the fill tubes and find replacements for the tents. Researchers lowered the amount of helium gas in the hohlraums to boost the energy absorbed by the target capsule and central hot spot by reducing backscatter losses and hot-electron production. This required them to learn about laser energy-coupling symmetry control in a new hohlraum regime. Studies also began on the use of different hohlraum shapes, such as the Rugby, I-Raum, and Frustrum, intended to improve implosion symmetry and increase energy coupling.

NIF’s diagnostics, coupled with rapid advances in computer modeling and simulation, provided detailed information on all aspects of the implosion, from incident and backscattered laser light to the x-ray drive provided by the hohlraum. The timing of shocks to compress the target, the uniformity of the capsule while imploding, and plasma conditions as it approaches decompression or stagnation provided key insights into experimental results.

In 2017, researchers led by Callahan and Hurricane launched a series of experiments labeled Hybrid-B, -C, -D, and -E. The experiments combined aspects of the most successful previous experimental designs and new understanding coupled with new target designs that pair larger capsules with smaller or reconfigured hohlraums.

The hybrid experiments benefited greatly from continuous improvements in laser technology, including steady increases in laser energy and power made possible by years of work to harden NIF’s optics against laser damage. The development of the Virtual Beam Line++ code, which calculates the light diffraction, amplification, and other behavior of laser light, enables scientists to calibrate for distortions in the laser beams and deliver the precise pulse shape required by experimenters. Other upgrades, such as automation of time-consuming manual activities, an advanced laser-alignment system, an integrated

suite of online tools, and methods for gleaning more data from a shot, steadily increased the rate of data generation.

2019–2020: With the beginning of the Hybrid-E program in 2019, helmed by designer Annie Kritcher and experimentalist Alex Zylstra, researchers made significant progress in coupling more energy to the target to improve compression and hot-spot pressure and temperature. An experiment in June 2019 tested large diamond capsules in compact hohlraums under ignition-relevant conditions (high laser energy and implosion velocity). The shot used CBET to control asymmetries caused by the larger capsule. The experiment significantly bettered the capsule-absorbed energy of NIF’s record-setting shots from the summer of 2017—from 150–200 kilojoules to more than 270 kilojoules—while maintaining the good symmetry and high velocity needed for a successful implosion. Similar but slightly lower coupling gains were achieved in the I-Raum campaign, which used smaller capsules.

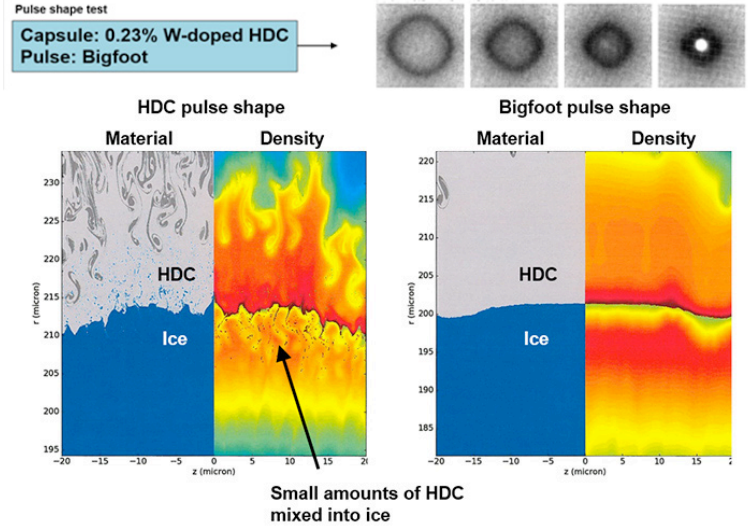
Advanced diagnostic and simulation technologies substantially improved understanding of the sources of implosion degradations, especially asymmetries and fuel contamination, or mix. A series of experiments conducted in 2019 tested the theory that including different types and amounts of dopants in the capsule shell could help control instability and reduce mix. The results were recorded using NIF’s CBI/SLOS “super camera”—the Crystal Backlighter Imager paired with the single-line-of-sight camera.

In addition, the Target Fabrication team developed new metrology and manufacturing tools and tested different carbon crystalline structures to substantially reduce surface and subsurface defects (called pits and voids) and thickness variations in the larger diamond target capsules needed for hybrid experiments.

Progress accelerated in November 2020 when Hybrid-E and I-Raum experiments achieved a burning plasma state for the first time, producing an energy yield of about 100 kilojoules, or nearly double the previous record. A high-velocity Hybrid-E implosion with an extended laser pulse generated hot-spot pressures of about 300 gigabars (300 billion atmospheres).

2021: On Feb. 7, 2021, a Hybrid-E experiment achieved a fusion yield of 6×10^{16} (60 quadrillion) neutrons and 170 kilojoules of fusion-energy output, a 70 percent increase over the November results. Experiments using the I-Raum achieved similar yields.

Then came the record-smashing Aug. 8 shot. Key factors in the experiment’s success included shrinking the aperture of the hohlraum’s laser entrance holes to curb energy losses; substantially reducing the



(Top) CBI/SLOS radiographs from an experiment in July 2020 during a “Bigfoot” implosion of a tungsten (W)-doped HDC capsule. The experiment was designed to test simulations (below) suggesting that the rapid acceleration provided by the “Bigfoot” pulse shape stabilizes the implosion against early-time instabilities, reducing mix.

defects in the target capsule; decreasing the size of the fill tube from five to two microns; and extending the laser pulse to effectively hold the implosion together longer and concentrate more energy in the hot spot.

In the experiment, alpha heating ignited fusion reactions that spread through the fuel in a self-sustaining thermonuclear burn wave, consuming almost 2 percent of the fuel. The shot produced an unprecedented 4.8×10^{17} (480 quadrillion) neutrons and more than 10 quadrillion watts of fusion power for about 100 trillionths of a second. The 1.35 megajoules of fusion-energy yield was eight times more than the February experiment and 25 times the record set in 2018.

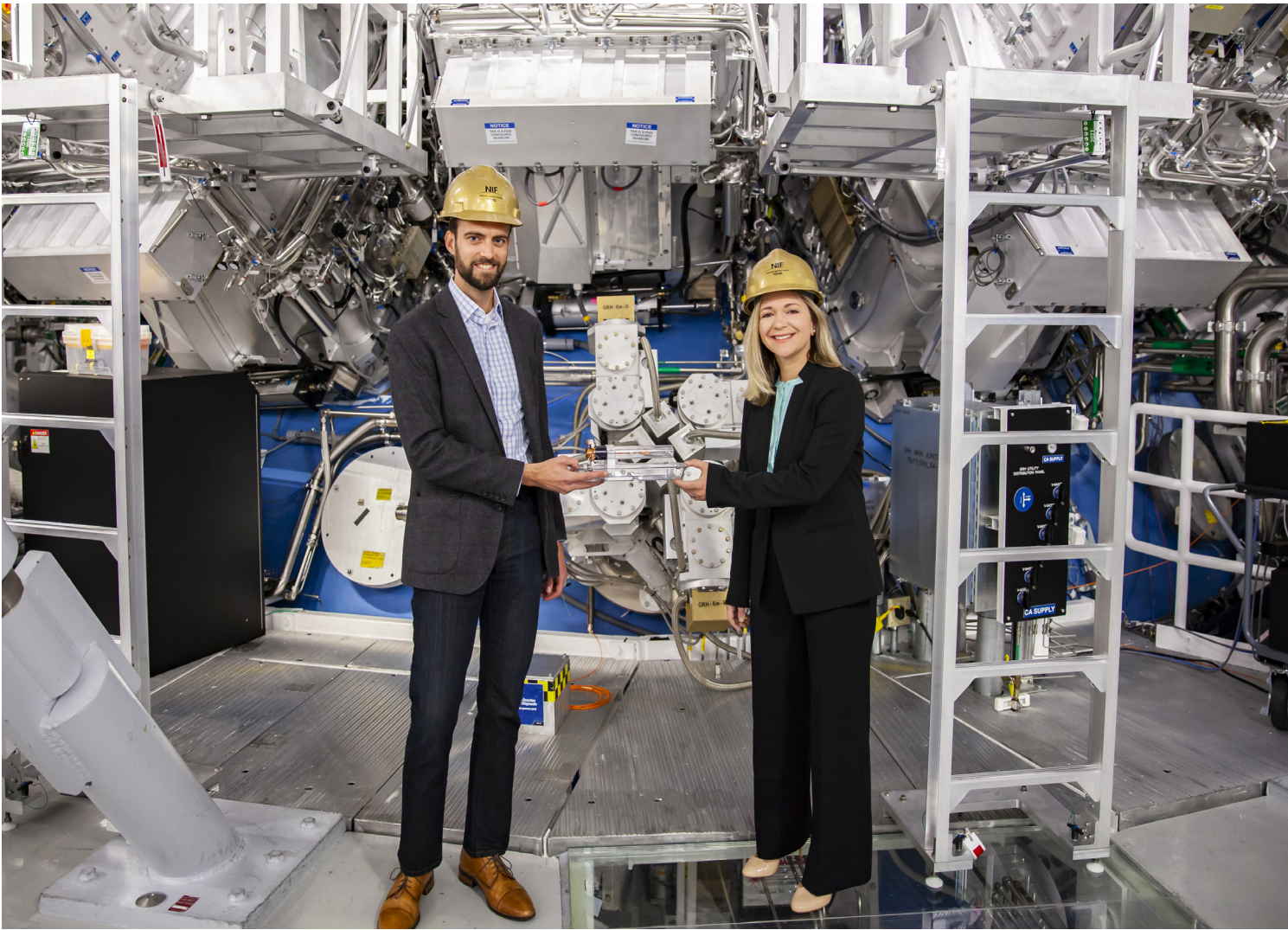
“This is a Wright Brothers moment,” Hurricane said.

“Our result is a significant step forward in understanding what is required for (fusion) to work. The fusion energy generated was almost six times the energy absorbed by the capsule and about 70 percent of the laser energy shot at the target. We got off the ground for a moment.”

“This has been an incredible challenge,” Edwards said. “So many extremely hard problems had to be understood and overcome across the

“We’re constantly improving the capability of the laser from the standpoints of how much energy and power we can generate, the precision with which we can deliver it, and how we can diagnose the experimental output. We also continually engineer improvements to operational efficiency, identifying anything that will make NIF more productive for the Stockpile Stewardship Program.”

NIF Director Doug Larson



Alex Zylstra and Annie Kritcher in the NIF Target Bay holding a NIF target. Credit: Mark Meamber

entire system to get to this point. Pretty much at every step we were pushing and expanding the envelope of the possible.

“The inventiveness and commitment of the many people over decades who made this happen never ceases to amaze me,” he added. “It’s been a privilege to share such a remarkable journey. It’s a big step for the future of the Stockpile Stewardship Program.”

The Aug. 8 result is being carefully analyzed and compared with subsequent

experiments to improve researchers’ ability to predict future performance and to assess possible increases in NIF’s energy and power to drive even higher yields.

The experiment was a milestone in NIF’s role within NNSA’s science-based Stockpile Stewardship Program, which was created in the 1990s to ensure the reliability and safety of the U.S. nuclear deterrent without the need for full-scale testing.

Herrmann said these results will help weapons scientists test and refine the computer models they use to better understand and assess the performance of the stockpile’s aging nuclear weapons. The higher yields also can contribute to near-term applications supporting NNSA’s nuclear-modernization program and studies of nuclear survivability, improve understanding of the thermonuclear burn process, and increase confidence in the

development of a future high-yield (100+MJ) facility to support stewardship.

“This is a regime that we’ve been working toward for a very long time,” Herrmann said. “It’s a massive change for not just our program, but for the national (stewardship) program. It’s really a testament to this Lab and our partnerships with many external partners.”

LLNL Director Kim Budil said the result “opens the door to exciting new NIF applications to support stockpile stewardship,

enables us to study robustly burning plasmas for the first time since underground testing ended, and creates new possibilities to get to much higher fusion yields on NIF.”

“There’s a lot more to learn, a lot more to think about, a lot more experiments to do,” Herrmann said. “It’s hard to imagine a more exciting time for this program.”

Along with the LLNL participants, researchers credited the experiment’s success to collaborators from Los Alamos and Sandia

national laboratories, General Atomics, the Laboratory for Laser Energetics at the University of Rochester, the Nevada National Security Site, the Department of Energy and NNSA, the academic community including MIT and Princeton, and international partners such as the UK’s Atomic Weapons Establishment and the French Alternative Energies and Atomic Energy Commission.

—Charlie Osolin

HOW RESEARCHERS ACHIEVED BURNING PLASMA REGIME AT NIF

After decades of fusion research, a burning plasma state—a critical step toward self-sustaining fusion energy—was achieved for the first time in a laboratory experiment in November 2020 and February 2021 at NIF.

The work was detailed in the cover article in the Jan. 27, 2022, issue of *Nature* titled, “Burning plasma achieved in inertial fusion.”

“Fusion experiments over decades have produced fusion reactions using large amounts of ‘external’ heating to get the plasma hot,” said experimentalist Alex Zylstra “Now, for the first time, we have a system where the fusion itself is providing most of the heating. This is a key milestone on the way to even higher levels of fusion performance.”

NIF’s 192 lasers tightly focus on a tiny fuel capsule suspended inside a cylindrical x-ray oven called a hohlraum. The heat from the x rays blows off, or ablates, the surface of the target fuel capsule containing deuterium and tritium. The capsule surface implodes, compressing and heating the deuterium-tritium fuel until the hydrogen atoms fuse, releasing neutrons and other forms of energy.

Getting fusion to work requires getting the power balance in the fuel right—there are always mechanisms that cause the plasma to

lose energy, while fusion and the implosion’s compression heat the plasma.

Fusion is a highly non-linear process and, in this regime, researchers now have the opportunity to rapidly increase performance—in fact, this burning plasma work was a key stepping stone to the 1.35-MJ yield produced on Aug. 8, 2021. Generating these burning plasmas on NIF enables novel stewardship science experiments on both the burn physics and stockpile applications using the higher yield.

Designing and conducting these experiments was the work of a huge multidisciplinary team, with more than 150 coauthors on this publication from LLNL and partner institutions. Confirming that researchers had actually entered the burning plasma regime required using some inferred metrics, where a combination of measured quantities was used from several key NIF diagnostics and models to infer the energy balance in the fusion fuel. This work was largely done by a working group that analyzed the hot spot, with conclusions validated by another working group of scientists at the Lab.

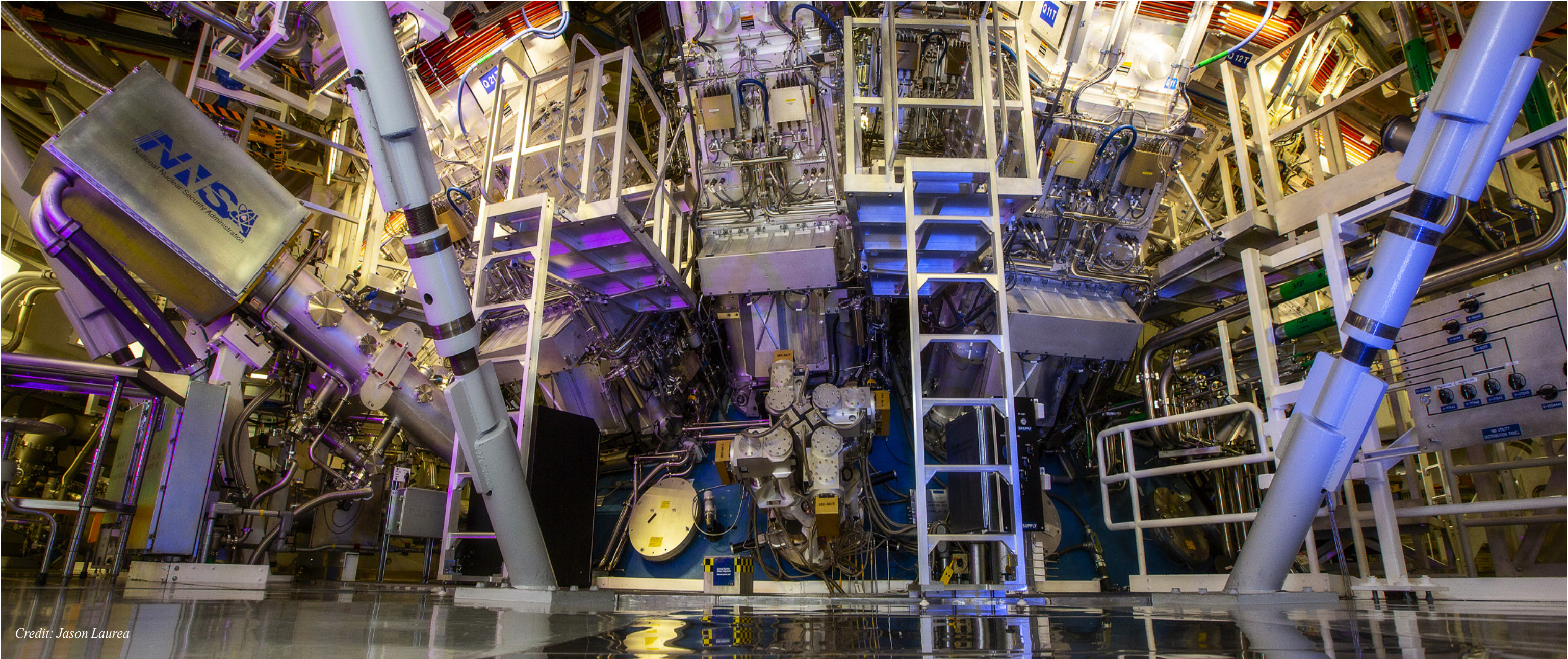
Reflecting the team effort, additional papers were published on burning plasma



Cover of the Jan. 27, 2022, issue of *Nature*. Image credit: Jason Laurea

experiments. A companion design paper was published in *Nature Physics* on Jan. 26, 2022. Further analysis of these experiments was also submitted for publication.

—Michael Padilla



Credit: Jason Laurea

Chapter 2

‘HYBRID’ EXPERIMENTS DRIVE NIF TOWARD IGNITION

Designing the experiment that brought NIF to the threshold of ignition on Aug. 8, 2021, was a multiyear problem-solving effort aimed at firing enough laser energy into the hot spot at the center of a NIF target capsule to trigger a self-sustaining burn wave of fusion reactions.

It was anything but easy. Inertial confinement fusion (ICF) researchers pursued a wide variety of experimental approaches over

the course of a decade, looking for ways to maximize the energy delivered by NIF’s lasers in the hohlraum, capsule, and hot spot. Those efforts culminated in the record-breaking shot that generated more than 10 quadrillion watts of fusion power for 100 trillionths of a second.

“The ICF program has steadily advanced our physics understanding and the technology over the last decade to improve performance,” said ICF Chief Scientist Omar Hurricane. The record shot “built on a decade

of research by an incredible team across the Lab and the wider community.”

The shot was part of a series of “hybrid” (high-yield, big-radius implosion design) experiments on NIF that couple the best elements of previous high-yield experiments with new understanding of the implosion process informed by rapid advances in diagnostic and modeling technology.

The strategy applies this knowledge in a new design based on the largest capsule size that can be fielded symmetrically within NIF’s current experimental limits while maintaining other important implosion properties.

The experiment’s success “demonstrates that NIF can provide access to the physics regime around ignition,” said Lawrence Livermore National Laboratory physicist Annie Kritcher, lead designer for the Hybrid-E experiments, the latest in the series. “Creating these conditions in the laboratory will significantly advance our understanding of what it takes to achieve energy gain higher than

required to initiate the reactions and provides access to a new experimental regime that was previously unattainable.”

*“This is a huge advance
for fusion and for
the entire fusion
community.”*

LLNL Physicist Debbie Callahan

Boosting Hot-Spot Energy Density

Although NIF is the world’s largest, highest-energy laser system, almost all the energy from the facility’s 192 laser beams is lost to wavelength conversion, x-ray production, backscatter, and other factors before it reaches the capsule. The concentration of

energy in the hot spot is one key to obtaining high levels of fusion performance and reaching the conditions required for ignition. Ignition is achieved when the heating power from alpha particles produced by fusion reactions in the hot spot overcomes the cooling effects of x-ray losses, electron conduction, and implosion expansion, causing a self-heating feedback loop in the fusion fuel and an explosive amplification of energy output.

Fluid instabilities, asymmetries, electron heating, hot-spot drift, and other “non-ideal factors” tend to “steal energy away from the system and waste it in various ways,” Hurricane said.

“Hot-spot drift and asymmetry prevent the kinetic energy of the implosion from being fully converted into internal energy at peak compression,” he said. “That’s basically wasted energy.”

Other factors that have degraded capsule implosions include the mixing of capsule material with the fusion fuel, seeded by target

capsule surface pits, subsurface voids and thickness inconsistencies, and instabilities caused by the tents that suspend the capsule inside the hohlraum and fill tube used to inject fuel into the capsule. These elements “take energy and turn it into x rays,” Hurricane said, “and it’s lost from the system through x-ray emission.”

The hybrid strategy is part of a multipronged NIF effort to couple more laser energy to the hot spot. It features new target designs that pair larger high-density carbon (diamond) capsules with smaller or reconfigured hohlraums as well as new laser pulse shapes aimed at enhancing the radiation temperature in the hohlraum. The Hybrid-E experiments recorded the highest coupled energy to the hot spot yet achieved, while maintaining the high stagnation pressure required for good performance.

“The strategy is to increase the capsule scale while you maintain the other key parameters such as velocity, adiabat (which determines the compressibility of the fusion fuel), coast time, stability, and symmetry,” Kritcher said. She noted that larger capsules are more challenging to implode symmetrically, especially in more efficient smaller hohlraums filled with a low level of helium gas (in previous campaigns, the gas was used to help control the growth of a bubble of hohlraum wall material that interfered with energy distribution). Low gas-fill hohlraums, however, provide the highest-performing implosions and reduce backscatter losses and hot-electron production, especially when also using a technique to improve energy distribution and shape control known as cross-beam energy transfer, or CBET.

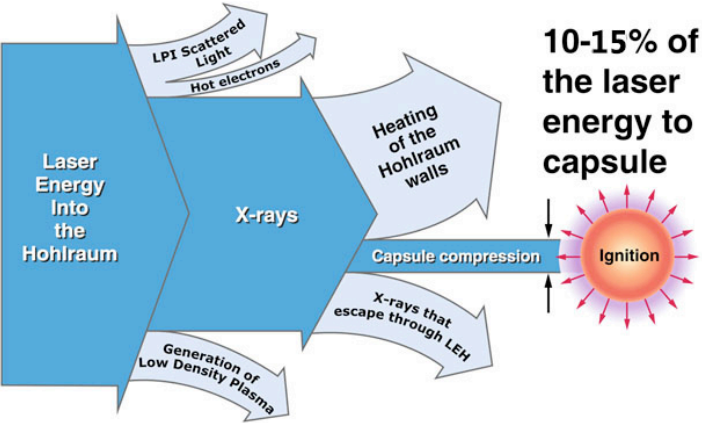
In CBET, the laser beams exchange energy as they overlap in the laser entrance holes. Slightly changing the wavelength of one or more sets of beams “moves energy from one set to another,” said lead experimentalist Alex Zylstra. “The amount of energy transfer can be tuned to balance the x-ray drive symmetry” so that energy is evenly distributed throughout the x-ray “oven” inside the hohlraum.

The Aug. 8 shot benefited from a simplified data-based model developed by LLNL physicist Debbie Callahan to guide design choices. “We used the data-driven model to make tradeoffs of different properties of the design to get us in the right ballpark of symmetry control,” Hurricane said.

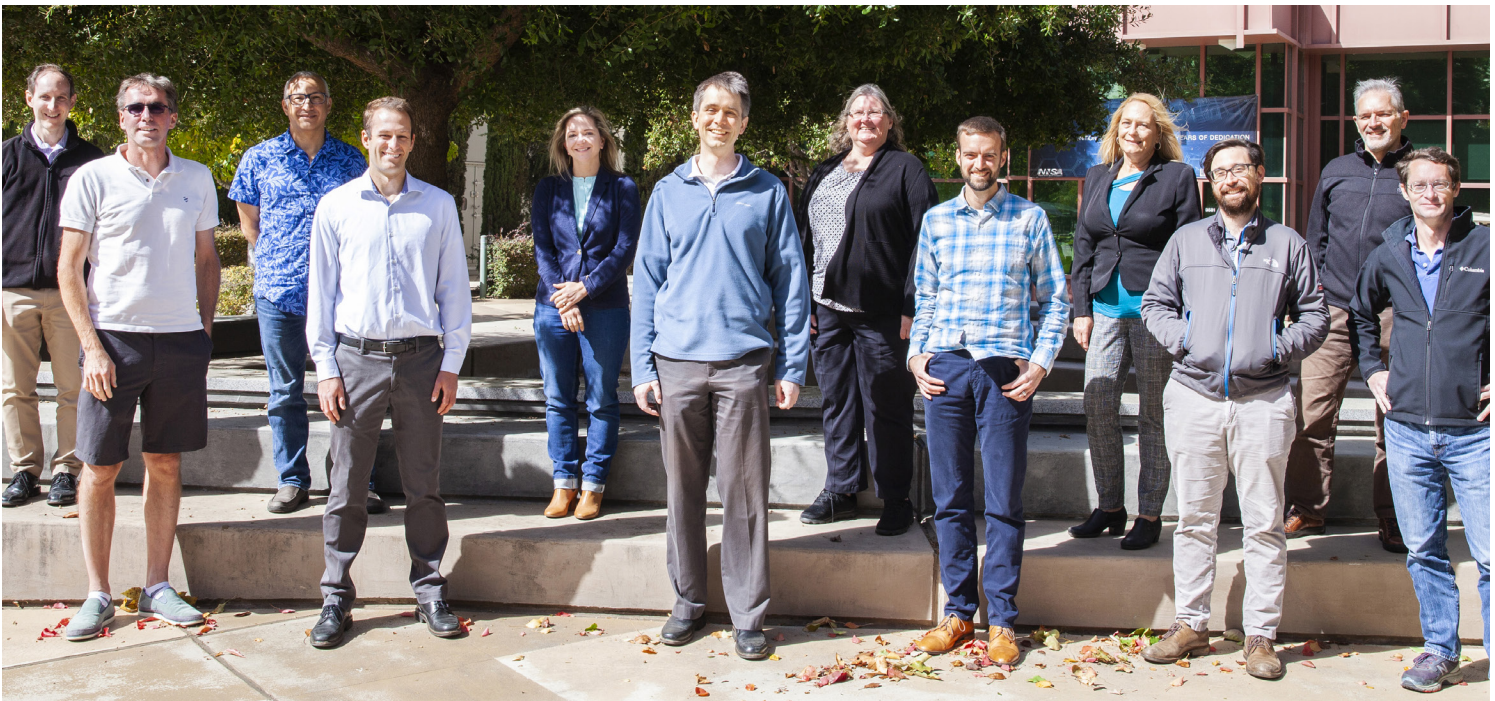
The lower gas fill also makes it easier to calculate and predict asymmetries using data-driven implosion models, Kritcher added, “enabling narrowing down the large design-parameter space much more quickly.”

The larger capsules—about 15 percent bigger than those used in previous high-yield experiments—are needed because a key parameter for ICF designs is the ratio of the hohlraum size to capsule size, called the case-to-capsule ratio (CCR). A smaller CCR enhances energy efficiency but makes it more difficult to control other aspects of the shot such as the symmetry of the x-ray drive on the capsule.

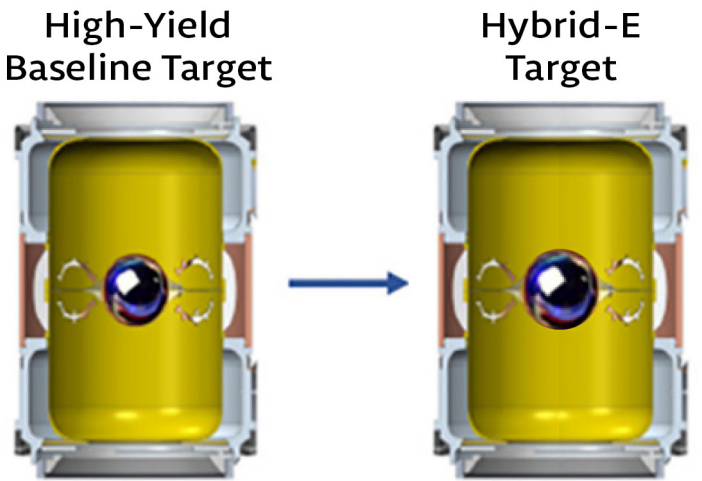
“By fielding these larger capsules at relatively small CCR,” Zylstra said, “we increase the coupling efficiency from laser energy to capsule-absorbed energy while controlling the implosion symmetry using wavelength detuning to control cross-beam energy transfer in the hohlraum.



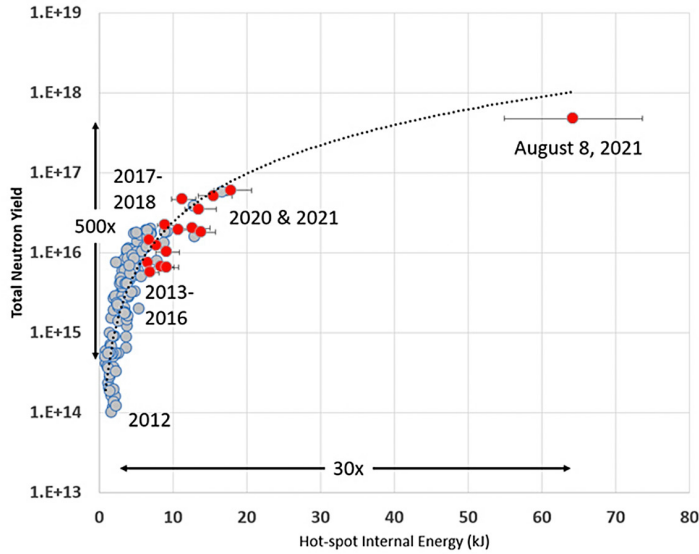
Simplified flow diagram showing NIF target capsule energy-coupling efficiency. The “laser energy” shown is after wavelength conversion from infrared to ultraviolet, which loses about half of the laser’s original energy. When the light reaches the hohlraum, it heats the inner walls and generates x rays that compress the fusion fuel, using up more than half of the 1.9 megajoules of ultraviolet light. After accounting for x-ray energy lost through the laser entrance holes (LEH), laser-plasma interactions (LPI) and backscatter, and other factors, in earlier experiments only about 150-270 kilojoules was absorbed by the capsule, and only about 10 kilojoules ended up in the fusion fuel.



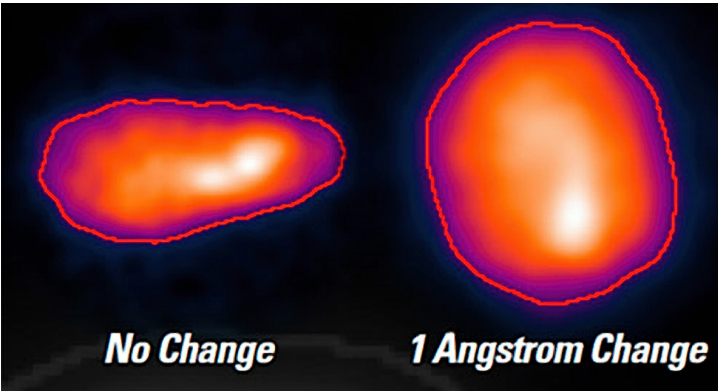
Members of the experimental team (from left): David Strozzi, Laurent Divol, Omar Hurricane, Chris Young, Annie Kritcher, Michael Stadermann, Debbie Callahan, Alex Zylstra, Denise Hinkel, Art Pak, Riccardo Tommasini, and Dan Clark. Not shown: Dan Casey, Chris Weber, Joe Ralph, Kevin Baker, Tilo Döppner, and Sebastien Le Pape. Credit: Mark Meamber



Comparison of a target used in previous high-yield experiments with a Hybrid-E target, which uses a capsule with a 15 percent larger radius and slightly larger hohlraum..



The relationship between hot-spot energy and neutron yield in NIF deuterium-tritium (ignition) experiments from 2012 through early 2021, with the highest-performing shots occurring in 2020 and 2021 (red dots indicate Hybrid-E shots). While not the only important variable—high hot-spot pressure is also important—the chart shows that doubling the hot-spot energy increases yield by a factor of four, demonstrating the importance of hot-spot energy to the success of NIF implosions. The Aug. 8 experiment achieved a hot-spot absorbed energy of about 65 kilojoules (kJ)—about 20 kJ from the implosion, and the rest from self-heating from the fusion reactions. Credit: Omar Hurricane



In a March 2019 experiment using cross-beam energy transfer (CBET), the wavelength of the laser light on a subset of beams was changed by one angstrom (one ten-billionth of a meter) and produced the result shown at right. Hybrid-E is the first campaign to employ this strategy in a low-gas-filled hohlraum with a diamond capsule, which is key for managing backscatter of laser light from the hohlraum.

This new design results in record values of the implosion kinetic energy and internal energy of the fuel at stagnation.”

The design was informed by terabytes of data from NIF’s suite of dozens of state-of-the-art nuclear, x-ray, and optical diagnostics, which dissected every aspect of the more than 170 DT experiments conducted since 2011. Those data were analyzed to improve understanding and enhance the predictive ability of implosion computer models.

The 1.35-megajoule experiment also benefited from efforts to increase the initial energy and energy balance of the NIF laser beams and improve the surface smoothness and thickness consistency of target capsules through new fabrication, metrology, and polishing techniques and innovative, more-stable capsule designs.

“To create the extreme conditions needed to achieve ignition,”

“The latest breakthrough was the result of a decade of scientific learning and progress, and key advances over the last two years in design, targets, diagnostics, modeling, and the NIF laser.”

NIF Director Doug Larson

Kritcher said, “these experiments require a great deal of precision in many aspects of the experiment, including laser delivery, target fabrication, and control of the symmetry of the imploding pellet and hydrodynamic instabilities. Many aspects need to come into place for the best experimental conditions, regardless of the intended design.”

Anatomy of a Milestone Experiment

Here are the key factors that led to the success of NIF’s 1.35-megajoule experiment:

- At 2:02 p.m. on Aug. 8, NIF’s 192 high-energy lasers poured 1.92 megajoules of ultraviolet energy—slightly more than researchers had requested—into the ends of the hohlraum, a gold cylinder about the size of a pencil eraser. The laser pulses had to be precisely repointed because researchers had shrunk the aperture of the laser entrance holes to prevent energy from escaping during the experiment.
- This made the hohlraum more efficient in coupling the laser energy, transformed into x rays, to the target capsule (the ablator) suspended in the hohlraum and filled with deuterium and tritium (DT), heavy isotopes of hydrogen. The radiation blew off, or ablated, the capsule’s outer surface, causing a rocket-like high-velocity implosion that compressed and heated the fuel until the hydrogen atoms began to fuse in the central hot spot, producing alpha particles (helium nuclei) and neutrons.
- The hohlraum’s increased efficiency enabled researchers to reduce the power at the peak of the laser pulse and use the energy to extend the pulse by a few hundred picoseconds (trillionths of a second). This

shortened the coast time between laser shutdown and the moment when the imploded target capsule stagnated at maximum compression—increasing the implosion velocity and stagnation pressure, concentrating more energy in the hot spot, and producing additional fusion reactions. The reduced coast time led to a smaller radius at peak velocity for the implosion, which is highly beneficial for the stagnation conditions. “The radius of peak velocity,” Hurricane said, “is essentially the radius where the decreasing ablation pressure outside the implosion is balanced by the increasing pressure due to convergence inside the implosion. Make that radius small and you win.” The extra laser energy, along with improved beam quality, accuracy, and stability, helped boost hot-spot pressure and temperature.

- The experiment used cross-beam energy transfer to control implosion symmetry. Slightly changing the wavelength of one or more sets of beams to control the exchange of energy as the beams crossed in the laser entrance holes helped balance the x-ray drive symmetry so that energy was evenly distributed throughout the hohlraum.
- The implosion was further enhanced by the uniquely high quality of the high-density carbon (HDC), or diamond, target capsule and the switch from a five-micron-thick to a two-micron-thick tube to fill the capsule with hydrogen fuel. Research showed that ablator material in capsules with many surface and interior defects tends to contaminate the fusion fuel, while thicker fill tubes cause instabilities—both damaging to the implosion. A thicker DT cryogenic-hydrogen ice layer along the inside edge of the capsule and additional tungsten dopant in the carbon helped increase hydrodynamic stability.
- As they all came together in the span of nine nanoseconds (billionths of a second), these changes and enhancements enabled the hot spot

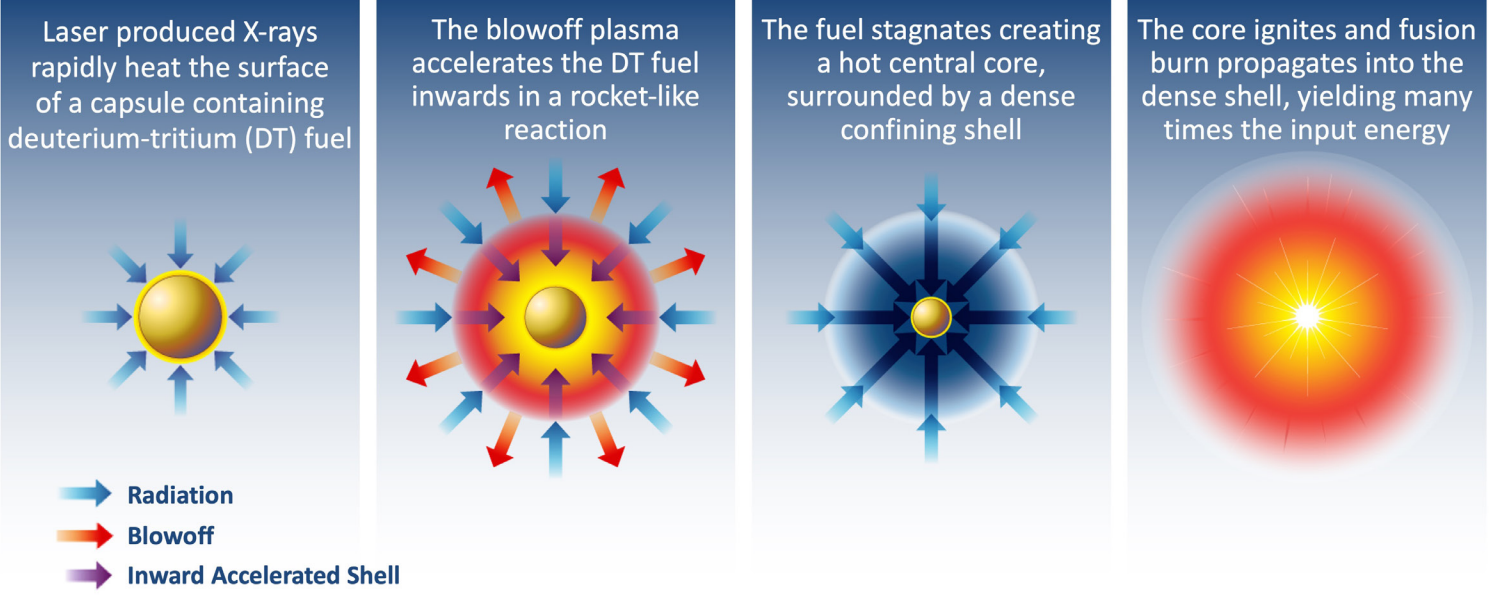
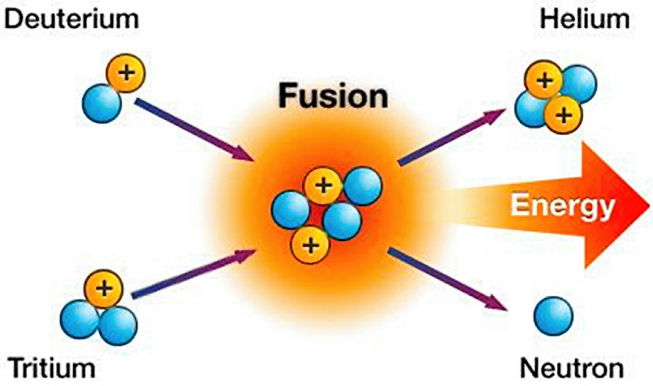


Illustration of laser-driven inertial confinement fusion. Credit: John Jett



In a fusion reaction, nuclei of the two isotopes of hydrogen, deuterium (containing one neutron and one proton) and tritium (two neutrons and one proton), are forced together by extremes of temperature and pressure and fuse to form a helium nucleus. In the process some of the mass of the hydrogen is released as energy.

to produce a record number of fusion reactions, unleashing a tsunami of high-energy alpha particles into the surrounding cold fuel. As the particles were absorbed, or “stopped,” this alpha-heating process ignited additional fusion reactions that spread through the fuel in a self-sustaining thermonuclear burn wave that consumed almost 2 percent of the fuel.

“Self-sustaining burn is essential to getting high yield,” Callahan said. “The burn wave has to propagate into the high-density fuel in order to get a lot of fusion energy out. This is a huge advance for fusion and for the entire fusion community.”

The result: The shot produced an unprecedented 4.8×10^{17} (480 quadrillion) neutrons and 1.35 megajoules of fusion-energy yield, eight times NIF’s previous energy record set by a Hybrid-E experiment in February, and 25 times the record from an HDC experiment in 2018. This was about 70 percent of the energy needed to meet the

formal definition of ignition established by the National Academy of Science in 1997.

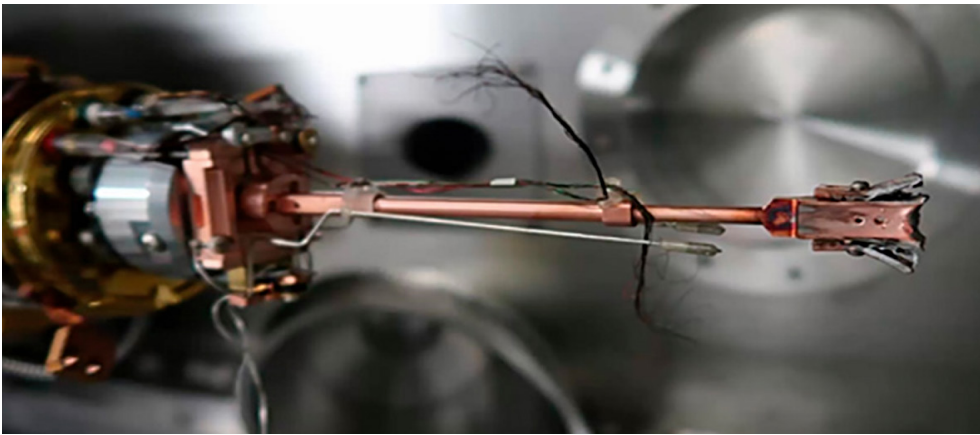
“ICF has been a continuous learning process,” Kritcher said. “Future experiments aim to understand the new physics regime we have recently accessed through advanced diagnostics and assessing performance reproducibility. Future work also includes continuing to improve on recent results by increasing the compression of the fuel and improving implosion efficiency by minimizing perturbations and continuing to develop the radiation drive.”

Besides Hurricane, Kritcher, Zylstra, and Callahan, the team members were Dan Casey, Dan Clark, Art Pak, Chris Weber, Chris Young, Joe Ralph (who led the work on smaller laser entrance holes), Kevin Baker, David Strozzi, Riccardo Tommasini, Denise Hinkel, Tilo Döppner, and former LLNL researcher Sebastien Le Pape. The experiment benefited from contributions by Nino Landen, John Edwards, and many other LLNL researchers; Abbas Nikroo, Michael Stadermann and

the Target Fabrication team; Jean-Michel Di Nicola, Steve Yang, and the laser operations team; and Andy MacKinnon, Alastair Moore, and the diagnostics team.

Also contributing were collaborators from Los Alamos and Sandia national laboratories, the Nevada National Security Site, General Atomics, the Laboratory for Laser Energetics at the University of Rochester, the academic community, industry, the Department of Energy and NNSA, and many other NIF partners in the fusion, plasma, and high energy density science communities.

—Charlie Osolin



The target after the Aug. 8 shot. Credit: Mark Meamber

RESEARCHERS DESCRIBE BURNING PLASMA TARGET AND LASER DESIGNS

One of the last remaining milestones in fusion research before attaining ignition and self-sustaining energy production is creating a burning plasma. In this state, the fusion reactions themselves become the dominant source of heating in the plasma, but do not yet overcome all mechanisms of energy loss.

In a paper featured in the Jan. 26, 2022, issue of *Nature Physics*, LLNL researchers and their collaborators described the experimental designs that achieved the first burning plasma state on NIF. The inertial confinement fusion experiments in November 2020 and February 2021 led directly to NIF’s record-breaking 1.35-megajoule shot on Aug. 8, 2021. The achievement also validates the work done decades ago to establish NIF’s power and energy specifications.

“In these experiments,” said LLNL physicist Annie Kritcher, lead author of the *Nature Physics* paper along with Chris Young, “we achieved, for the first time in any fusion research facility, a burning plasma state where more fusion energy is emitted from the fuel than was required to initiate the fusion reactions, or the amount of work done on the fuel.”

This was achieved through an energy feedback process called self-heating, in which the plasma created by a high-velocity implosion of a NIF target capsule heats itself. When the energy from self-heating exceeds the energy that was injected to initiate the fusion reactions, the plasma enters a burning plasma state.

Creating this new energy regime in a controlled laboratory setting is of great scientific importance for fundamental fusion research as well

as for the National Nuclear Security Administration’s science-based Stockpile Stewardship Program.

The ICF designs enabled the achievement of burning plasma by developing more efficient ways to drive larger-scale fusion targets to the same extreme conditions required for significant fusion to occur within the current experimental confines of NIF. By increasing the scale while maintaining high levels of plasma pressure, the team was able to ultimately deliver more of the initial laser energy directly to the fusion plasma and jump-start the burn process.

In doing so, the team found novel ways to control implosion symmetry by transferring energy between laser beams in a new way and by changing the target geometry. The designs were generated and optimized using a combination of theory, computational modeling by LLNL’s HYDRA multi-physics radiation-hydrodynamics code, and semi-empirical models informed by experimental data.

“We learned where we could and could not trust the modeling and when to rely on semi-empirical models,” Kritcher said. “We also found that keeping the driver pressure up longer (with a longer laser pulse) relative to the time it takes the target to implode was important for maintaining a high plasma pressure.

“Without this pressure, and enough energy coupled to the hot dense plasma, we would not reach the extreme conditions required for significant fusion.”

The design work supporting these ICF platforms began several years ago. The teams first recognized technical issues limiting performance,

explored many different options to solve these technical problems, presented choices to the broader team, and down-selected.

Designs were updated continuously with data from tuning experiments and ultimately put to the test in high-performance experiments with fusion fuel.

These designs are typically generated by a lead designer with input from the broader interdisciplinary team including designers, experimentalists, theorists, and facility experts (laser and target). Each new iteration builds on decades of previous work, solving an existing problem or incorporating a new idea that advances fusion performance to a new level.

Through the design changes outlined in the paper, researchers were able to increase the size of the target and still maintain the same levels of extreme plasma pressure that were achieved at smaller scale, all while operating at the maximum available NIF energy.

“There is much work yet to be done and this is a very exciting time for fusion research,” Kritcher said. “Following this work, the team further improved hohlraum efficiency in both platforms, increasing hot spot pressure which resulted in higher performance and the record 1.35-MJ experiment.”

Kritcher explained that this new platform is now the “base camp” for a significant fraction of ongoing programmatic work, focusing on understanding the sensitivity of this new regime, improving robustness of the platform, and further increasing the energy and pressure of the fusion hot spot.

“This will be explored through a variety of ideas to increase fuel compression and energy coupling,” she said.

A companion paper by lead authors Alex Zylstra and Omar Hurricane was published in *Nature* on Jan. 26, 2022. The paper, “Burning plasma achieved in inertial fusion,” chronicles the research that produced a burning plasma regime for the first time in a laboratory experiment.

—Michael Padilla

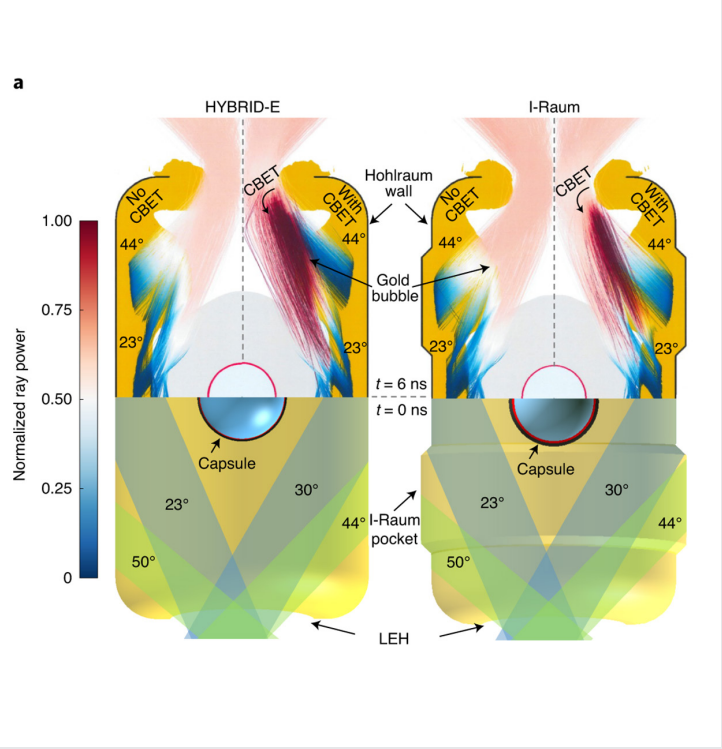
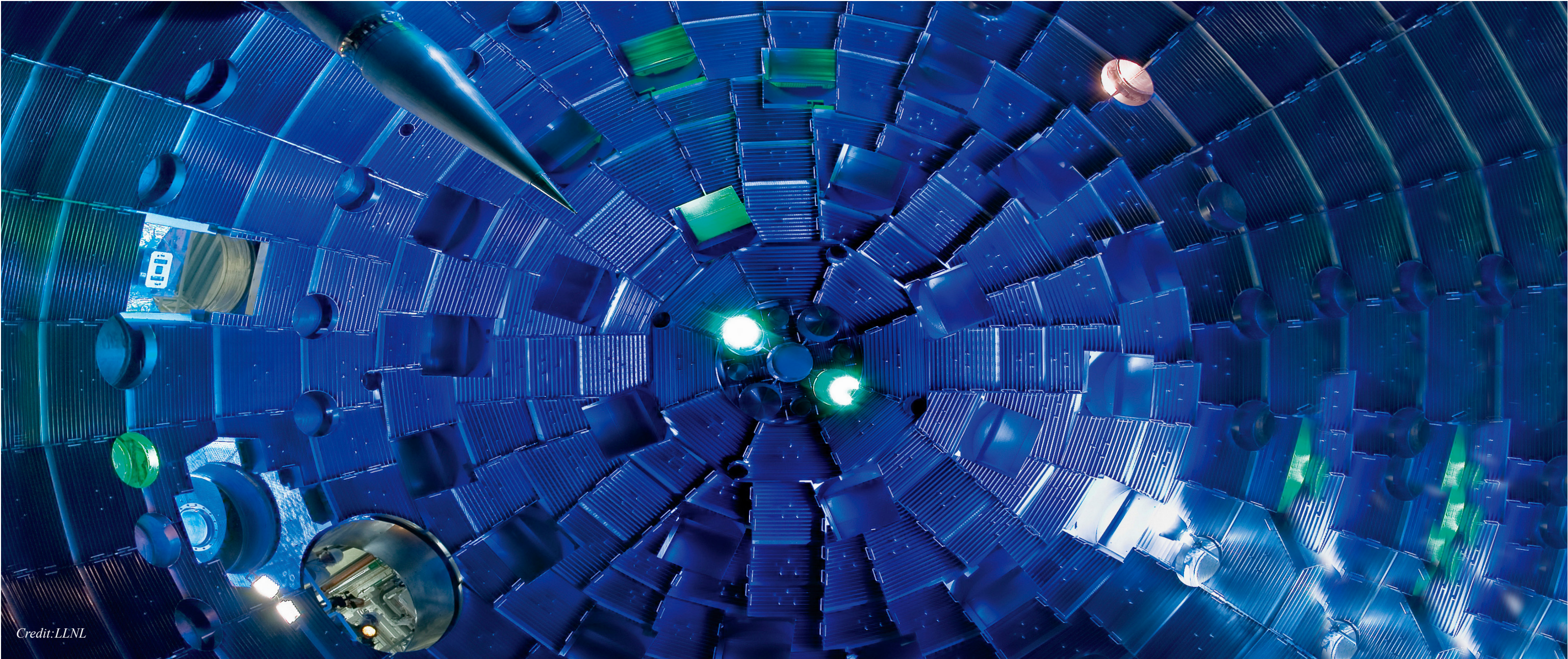


Illustration of the two ICF designs that first reached the burning plasma regime. The Hybrid-E hohlraum, left, effectively leveraged cross-beam energy transfer (CBET) to control implosion symmetry. The I-Raum shaped hohlraum, at right, adds “pockets” to displace the wall and the material blowoff that obstructs laser beam propagation away from the capsule, controlling implosion symmetry through a combination of geometry and CBET.



Credit: LLNL

Chapter 3

NIF DIAGNOSTICS PLAYED KEY ROLE IN FUSION MILESTONE

NIF’s highly specialized and sophisticated measuring instruments known as diagnostics were integral to the record-setting inertial confinement fusion (ICF) experiment that produced 1.35 million joules (MJ) of fusion energy.

The Aug. 8, 2021, breakthrough marked the culmination of a series of advances in diagnostics dating back to the mid-1990s, encompassing

contributions from the entire high energy density (HED) science community and the support of all NIF users.

“It takes a village—most definitely,” said Andrew MacKinnon, the lead scientist for NIF diagnostics. “These are among the most well-diagnosed experiments in the field of HED science.”

The advances have brought researchers to the threshold of the National Academy of Sciences’ formal definition of ignition: a NIF

implosion that produces as much or more fusion energy than the amount of laser energy delivered to the target. NIF fires 192 high-energy lasers into a fusion target the size of a pencil eraser and is capable of producing temperatures of more than 100 million degrees Kelvin and pressures of hundreds of billions of Earth atmospheres.

The NIF diagnostic suite dissects all aspects of the experiment, enabling researchers to develop a physical understanding of what is actually occurring, which can be compared to models and used to inform future experimental designs. The diagnostics provide detailed information on how much laser energy is delivered and coupled to the target, how uniformly the capsule is compressed, how well the implosion performs,

and how much fusion energy is released by the compressed capsule.

These diagnostics have enabled new measurement capabilities that have increased understanding of degradations to ICF implosions, such as asymmetries, mixing of capsule material in the hot spot, and fuel and capsule thickness variations, and have helped to develop mitigations.

“Diagnostics are an important measurer of integrated performance,” said ICF Chief Scientist Omar Hurricane. “That includes not only what we thought the design would do, but also the impact of the targets and, in particular, any imperfections in the target and in the laser and the laser delivery, if that happens.”

Scientific Diagnostic Leader Joe Kilkenny, who has led the NIF diagnostics team for a decade, likened the role of the facility’s

diagnostics to those used in cars. While NIF has five times more diagnostics than cars, both types come in two broad categories—performance optimization and identification of issues.

The first category allows fine-tuning on expected performance. A car’s fuel, throttle, and knock sensors allow precise timing of fuel ignition. On NIF, high precision in implosion symmetry and adiabat (fuel compressibility) control is achieved by monitoring and correcting the shape of the implosion and by timing the series of small shocks that compress the fuel.

The second category monitors system performance and provides notification of unexpected occurrences, according to Kilkenny. Diagnostics on a car may trigger emergency braking or suggest checking the

cooling system. NIF diagnostics can warn of imperfections in the target or the laser that require mitigation.

Data from NIF’s suite of state-of-the-art nuclear, x-ray, and optical diagnostics were used to scrutinize the more than 170 ignition experiments conducted since 2011. The data were analyzed to provide vital insights, build understanding of all stages of the ICF implosions, and inform the computer models and simulations that guide the design of future experiments.

One important diagnostic is the 3D neutron-imaging system (NIS), developed by researchers at Los Alamos National Laboratory (LANL) in collaboration with Lawrence Livermore colleagues. NIS data is used to provide a 3D analysis of the neutron-emitting hot spot and the surrounding deuterium-tritium fuel, an important measure of the quality of the implosion.

About 20 diagnostics were used in the 1.35-MJ shot, including time-integrated and time-resolved x-ray imaging from three different lines of sight; time-integrated neutron imaging from three lines of sight; neutron spectra measurements from six lines of sight; absolute neutron yield via nuclear activation measurements; 48 real-time nuclear activation detectors that are used to infer DT fuel uniformity; and time-resolved x-ray and neutron emission and soft x-ray measurements from the hohlraum.

The researchers said all diagnostics performed well on the experiment, but noted that in the future, some instruments not used on high-yield shots will be removed from the target area to prevent sensor degradation. Meanwhile, LLNL researchers and their colleagues continue to develop new diagnostics that are capable of operating in the presence of high-energy neutrons. Measuring the time evolution of ion temperature and electron temperature during ICF implosions are other high-priority goals for additional diagnostics.

Plans for the NIF diagnostic suite began in the mid-1990s, building on diagnostic expertise that originated at the Nevada Test Site and was further developed at LLNL’s NOVA laser, NIF’s predecessor. In 2013, a new multi-laboratory diagnostic collaboration called the National Diagnostic Working Group was established. Its goal was to continue developing state-of-the-art diagnostics for all the HED laboratories funded by the National Nuclear Security Administration (NNSA).

NIF now has more than 120 diagnostics directly funded over the last decade by NNSA. Many key R&D elements of these diagnostics have also been supported by funding from Laboratory Directed Research and Development (LDRD) programs at LLNL and other NNSA laboratories.

The diagnostics, which are used for a wide variety of HED experiments, have benefited from decades of experience and ongoing collaborations with national and international partners, including LANL, Sandia National Laboratories, the University of Rochester’s Laboratory for Laser Energetics, the Massachusetts Institute of Technology, UC Berkeley, General Atomics, the Nevada National Security Site, National Security Technologies, LLC, and the atomic energy agencies in the U.K. and France.

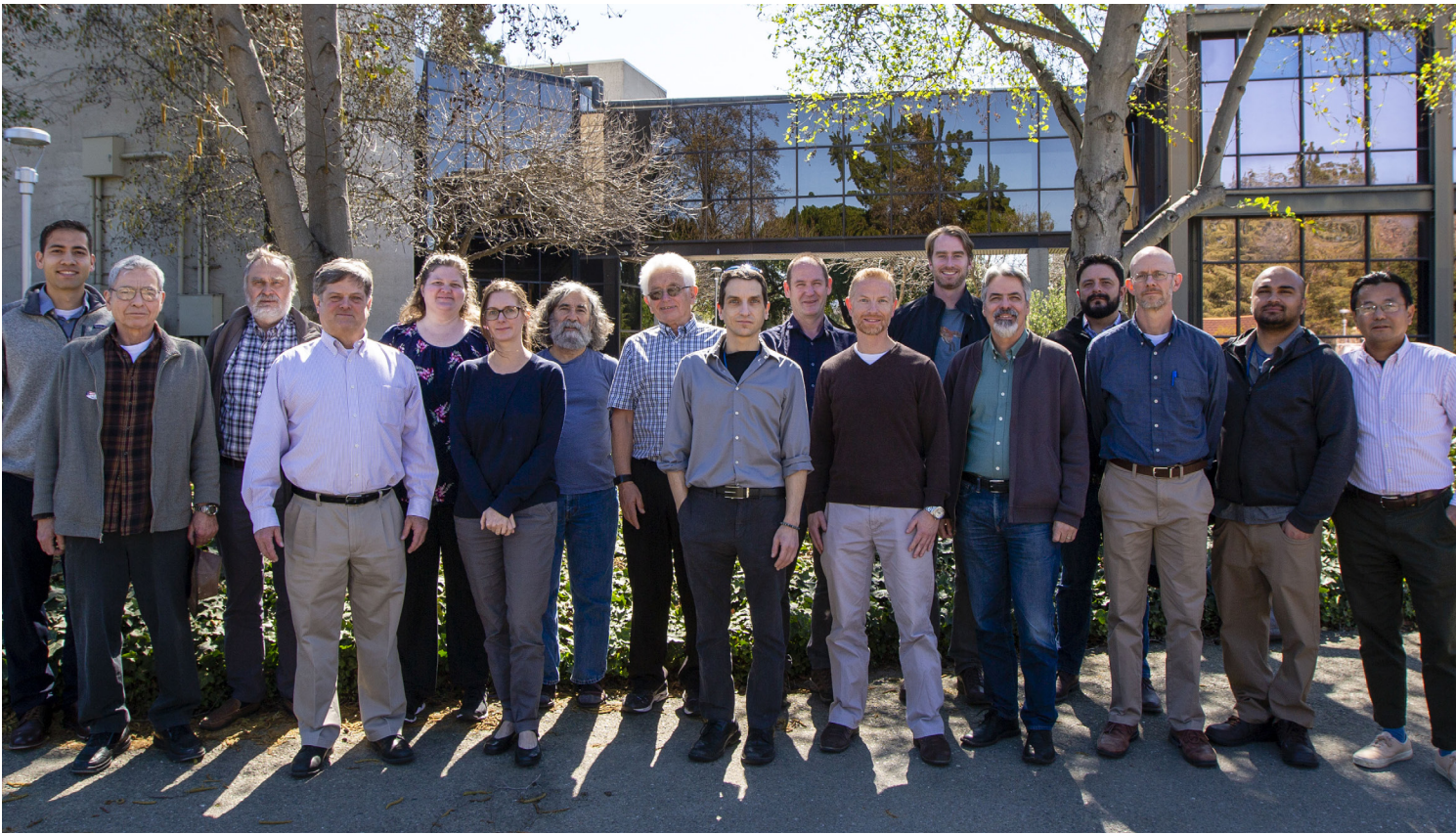
—Jon Kawamoto



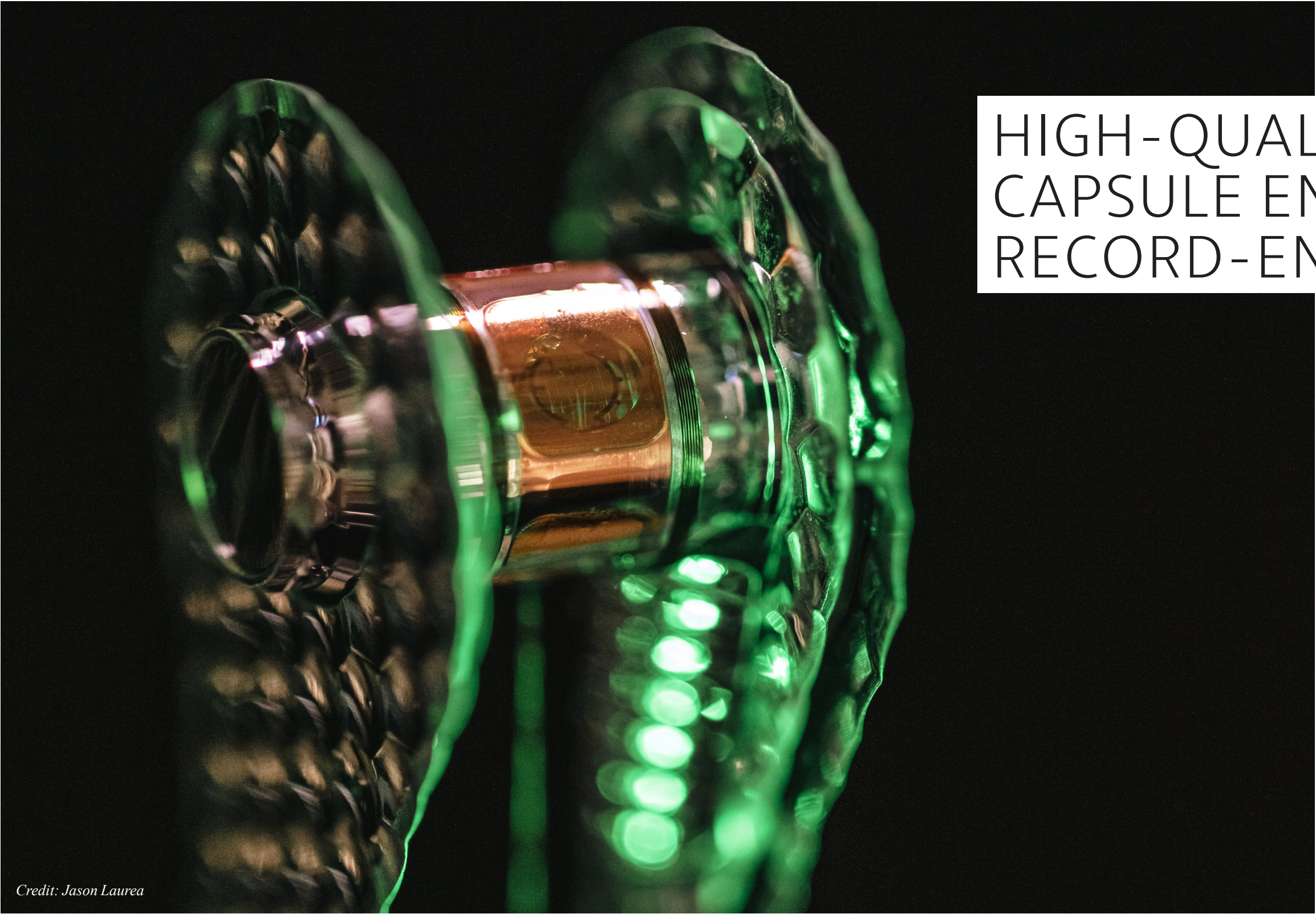
Joe Kilkenny, left, and Terry Hilsabeck of General Atomics examine the drift tube in NIF’s groundbreaking single-line-of-sight (SLOS) framing camera. The drift tube is analogous to the slow-motion feature on a standard camera. Credit: Kenneth Piston



Target-area operator Bill Board removes the neutron-imager snout from a diagnostic instrument manipulator. The NIF neutron-imaging system (NIS) produces an image of the source distribution of high-energy, or primary, neutrons and lower-energy “down-scattered” neutrons produced by fusion reactions in a NIF implosion. This enables researchers to determine hot-spot size and fuel asymmetry and to infer the cold-fuel areal density, a measure of the combined thickness and density of the fuel shell. Credit: James Pryatel



Members of the NIF nuclear-diagnostics team (from left): Eddie Mariscal, Richard Biota, Petr Volegov, Thomas Murphy, Valerie Fatherley, Kelly Hahn, Ed Hartouni, Joe Kilkenny, Dave Schlossberg, Andy Mackinnon, Alastair Moore, Shaun Kerr, David Fittinghoff, Jorge Carrera, Joseph Caggiano, Justin Jeet, and Wenhai Yang. Credit: Jason Laurea



Credit: Jason Laurea

Chapter 4

HIGH-QUALITY DIAMOND CAPSULE ENHANCED NIF’S RECORD-ENERGY SHOT

Among the factors contributing to NIF’s record-smashing 1.35-megajoule (MJ) energy-yield shot—besides innovative experimental design and advances in diagnostics, modeling, and laser precision—was the quality of the high-density carbon (HDC), or diamond, target capsule used in the experiment.

In terms of surface and internal defects and unwanted contamination, “this was the best diamond capsule they (the researchers) ever shot,” said Abbas Nikroo, NIF & Photon Science target fabrication program manager. “How much that was a player versus the changes that were made from a physics point of view, that’s something that we’re going to be piecing together for some time to come.”

The capsule had 10 times fewer surface holes, or pits, and subsurface voids, as well as fewer contaminating high-Z (high-atomic-number) inclusions, than the capsule used in NIF’s previous record-energy experiment in February 2021, which produced only one-eighth the energy of the August shot. The capsule defects were thought to substantially contribute to the amount of capsule material mixing into the imploding fuel, preventing it from being compressed properly and reducing the hot-spot fusion rate below that required for ignition. Mix has been one of the most important factors preventing NIF’s goal of ignition from being reached; ICF researchers estimate that, on many shots, hot-spot mix can reduce energy yield by 40 percent, and sometimes much more.

Developing the high-quality capsule was a multiyear challenge for the LLNL Target Fabrication team, working in close collaboration with General Atomics (GA) of San Diego and Diamond Materials of Freiburg, Germany.

“That work is not only focused on making the material better,” said LLNL chemist Michael Stadermann, deputy program manager for

target fabrication, “but also on being able to measure the imperfections better so we can quantify the improvements.”

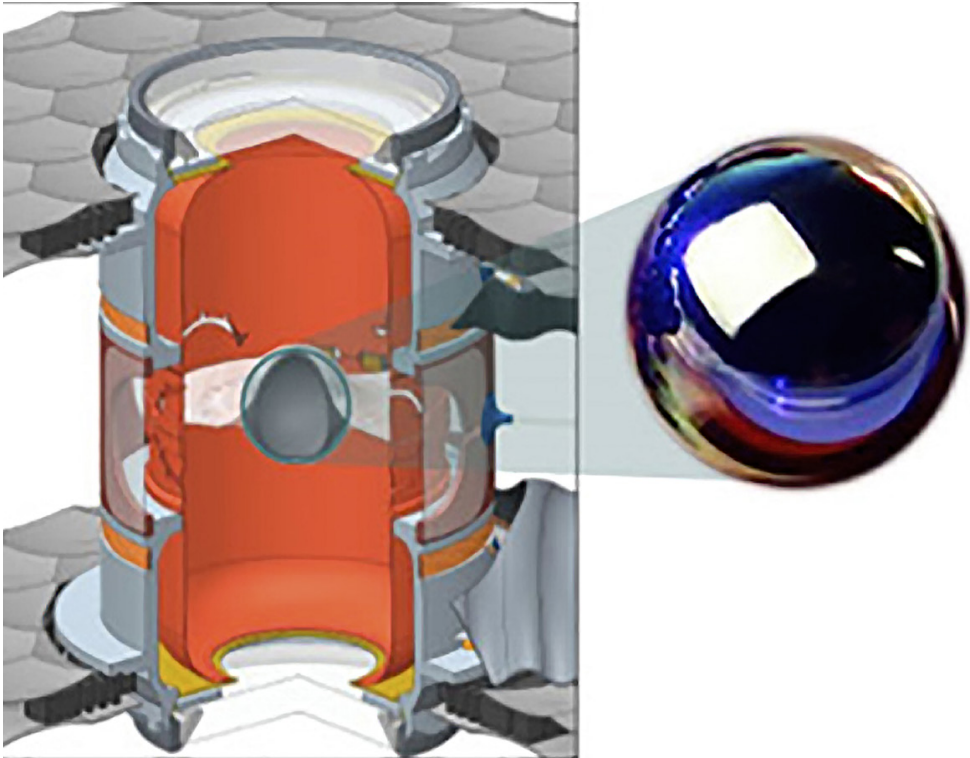
The team received a boost from the metrology expertise of LLNL optics and materials science researchers, who spent the past decade developing techniques to eliminate flaws in NIF’s optics so they can withstand the intense energy of 192 powerful lasers.

Along with the capsule, two other target-related factors played important roles in the August experiment:

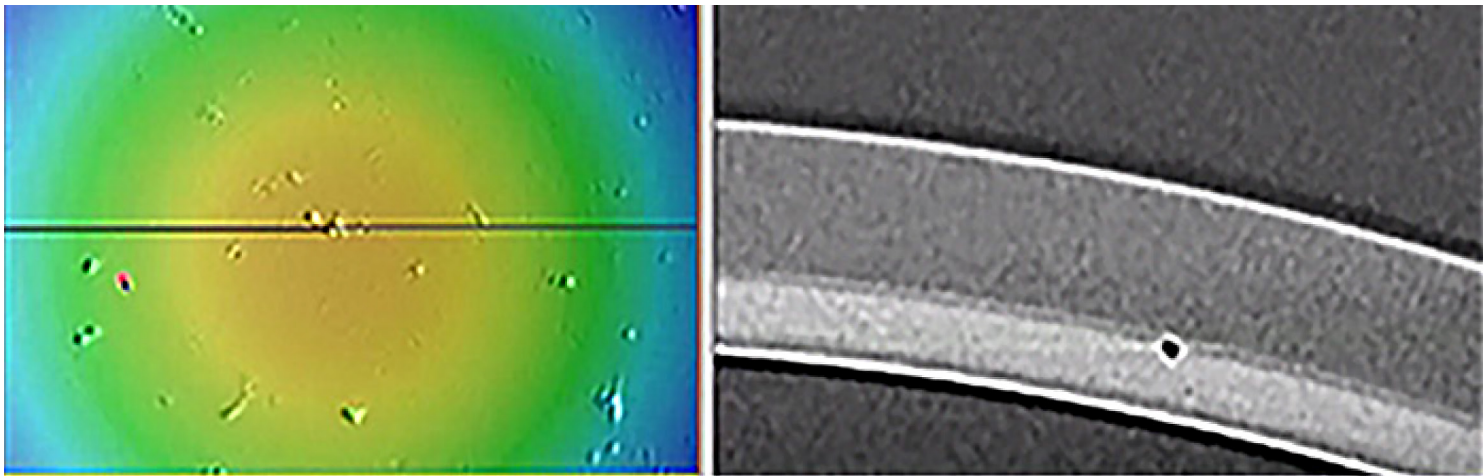
- A new hohlraum design with smaller laser entrance holes limited the loss of energy escaping through the holes during implosion, improving hohlraum efficiency—the amount of energy coupled to the capsule—and enhancing fuel compression and hot-spot pressure.

- A tiny two-micron-diameter fill tube was used to inject DT fuel into the capsule, limiting the tube’s contribution to implosion instabilities. The February shot used a five-micron fill tube—much thinner than the tubes used in early NIF experiments, which ranged from 10 to 44 microns in diameter.

The use of synthetic diamond capsules, produced by a process called plasma-assisted chemical vapor deposition (PACVD), was first proposed by LLNL scientists more than a decade ago. They came into routine use



In NIF inertial confinement fusion (ICF) experiments, laser beams enter a hohlraum through laser entrance holes at the top and bottom and strike the hohlraum’s inside walls. The resulting x rays ablate, or blow off, the surface of a tiny capsule, the ablator, containing deuterium and tritium (DT) fuel, causing a high-velocity implosion that fuses the hydrogen atoms and releases large amounts of energy. ICF target capsule shells may also contain internal layers with dopants that increase x-ray absorption. Precise control over dopant concentrations and thickness uniformity are continuing target fabrication challenges.



(Left) Holographic microscope image showing pits on the capsule surface. (Right) Tomographic image showing an internal void.

on NIF in the mid-2010s as ICF researchers searched for ways to improve on the disappointing performance of early experiments that used polymer (CH) capsules. Simulations led researchers to conclude that diamond, with its higher density, had the potential to outperform other target materials in terms of energy efficiency and implosion stability, thus making ignition more likely.

Diamond capsules were used in 2016–2018 for high-performing HDC experiments and in the “Bigfoot” shots in 2017 and 2018 that traded compression for implosion velocity.

“The benefit of a diamond material is it has better rocket (implosion velocity) efficiency and better ablation pressure than CH,” said ICF Chief Scientist Omar Hurricane, “so for a given amount of laser energy and a given amount of x-ray drive, it ablates better. That gives us a chance to get to higher implosion velocities for a fixed amount of laser energy.”

While the early diamond capsules performed well, problems arose when researchers requested larger capsules for the series of “hybrid” (high-yield big-radius implosion design) experiments that began in 2017.

“We were surprised right away by the capsule quality when we scaled those capsules up,” said Hurricane. “The quality degraded severely, and that was a shock to everybody.

“What we want is a perfectly smooth, or nearly perfectly smooth capsule, but instead we got something that looks like the surface of the moon. And through the thickness of the capsules, we have voids, so it’s a porous or Swiss cheese-like material, rather than solid. All of those imperfections are seeds for instability.”

“The first problem we had,” Stadermann said, “was that we didn’t really understand what the problem looked like. Pits were

“It was like a Sherlock Holmes mystery. It took a long time to understand where those problems were coming from.”

ICF Chief Scientist Omar Hurricane

always there, but we got those to a greater degree in those newer shells. We initially saw big voids—they were plainly visible in the radiographs—and so we got rid of them. Then we saw smaller voids, and those were much harder to quantify.”

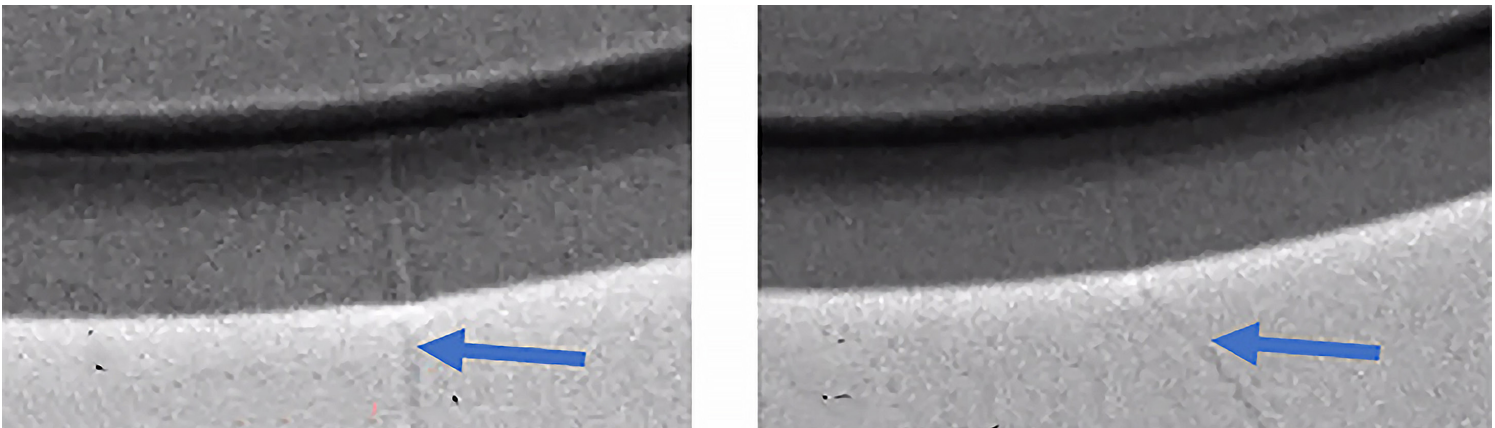
The team set about developing new measurement methods to improve their

knowledge of the size, extent, and location of the defects. Target Fabrication team member Tom Braun enlisted the help of NIF & Photon Science researcher Laura Mascio Kegelmeyer and her team, who had pioneered an automated technique for finding imperfections in NIF optics, to create a software algorithm for locating voids much more quickly and accurately than by manually inspecting a stack of thousands of images.

To overcome the limitations of standard measurement techniques that sample only small areas of the capsule at a time and could miss large pits and voids in other areas, researcher Haibo Huang and his team at GA developed a scanning technique called digital holographic microscopy that allows high-speed 3D surface imaging.

The question was, “How do we map the entire surface?” Stadermann said. “This holographic microscope allows us to scan a full shell in 30 minutes. With confocal microscopy, that would take five days.”

At about the same time, the team discovered a way for mitigating the pits “almost by accident,” he said. While investigating the source of the pits with Diamond Materials, “we learned that if you put a thin layer of fresh diamond onto the polished surface, you actually get a very clean surface.” The Target Fabrication S&T team continued to work with Diamond Materials to mitigate surface and



(Left) The five-micron fill tube used in the Feb. 7, 2021, experiment (an average human hair is about 70 microns in diameter). (Right) The two-micron tube used on Aug. 8. The thinner tubes are challenging to fabricate and extremely fragile, as shown by the bend that develops as the capsule cools.



A diamond capsule inside a NIF hohlraum. Simulations highlighted the advantages of short laser pulse lengths for maintaining symmetric x-ray drive conditions, as well as the importance of efficient energy coupling from the hohlraum to the capsule. Diamond capsules were best at meeting these requirements. Credit: Jason Laurea

bulk defects while expanding the range and concentration of dopant materials. In a collaboration with Rockwell International professor Satish Bukkapatnam at Texas A&M University, the team also employed new metrology instruments

that use MEMS (micro-electromechanical system) vibration sensing methods to detect specific anomalies in the polishing process. They worked to address the root causes of the anomalies through process innovations.

Along with defects, Dan Casey and his colleagues found that thickness non-uniformities can cause 3D asymmetries that rob energy from the capsule’s central hot spot. There have also been problems injecting the correct amount of tungsten dopant into the

shell, and “dopant variability can exacerbate hydrodynamic instability,” Hurricane said.

“It was like a Sherlock Holmes mystery,” he said. “It took a long time to understand where those problems were coming from. A lot of investigation has to go on to identify and understand the problems, propose solutions, test those solutions, and find the solutions that work. Sometimes you get lucky—the first thing you try works. But more often than not, you don’t luck out on the first try.”

The team also spent months trying to determine the optimal grain structure in the diamond material. At first, microcrystal diamond, with larger, micron-scale crystals, had fewer defects than nanocrystal material but was more difficult to inject with dopant. A breakthrough came after several Target Fabrication team members identified an issue in the coating process during a visit to Diamond Materials. Materials chemist Juergen Biener, an originator of the diamond capsule concept, then devised an innovative solution that led to high-quality nanocrystal capsules.

“That worked spectacularly well,” Stadermann said. “We were hoping to get nanocrystalline material as good as microcrystalline, but it was actually much better.”

The team started making capsules with the new process in December 2020, and the first was used in the Aug. 8 experiment. It wasn’t perfect; the shell still had a few hundred small pits and about 100 small voids—but still was nearly 100 times better than the capsules produced two years ago.

Capsule thickness issues contributed to a small amount of Mode 1 asymmetry (hot-spot drift), but “average capsule uniformity has also been improved to what may be a practical lower limit of about 200 nanometers,” Nikroo said. “Some of the batches used in the last two years were as large as 1,000 nanometers and exhibited what seems to be a clear (asymmetry) effect.

“The measurement technique was improved to ascertain this nonuniformity with greater precision and accuracy of less than 100 nanometers,” he added, “also due to the efforts of Haibo Huang and colleagues at GA.”

The Downside of Diamond

Despite the success of the 1.35-MJ record shot, diamond may not turn out to be the capsule material that propels NIF the rest of the way to its goal of ignition—when an experiment produces as much or more fusion energy than the amount of laser energy delivered to the target (about 1.9 MJ in ignition experiments).

Because of their crystalline structure, diamond capsules are more prone to seeding hydrodynamic instabilities during implosions, Hurricane said. “That forces us to create a pulse shape that hits the capsule with a very strong first (laser) shot to try to melt all of that crystal structure before the implosion really takes off, which alleviates some of the instability seeds.”

The strong first shock reduces instabilities but increases the fusion fuel’s adiabat (resistance to compression). “Because we have instability

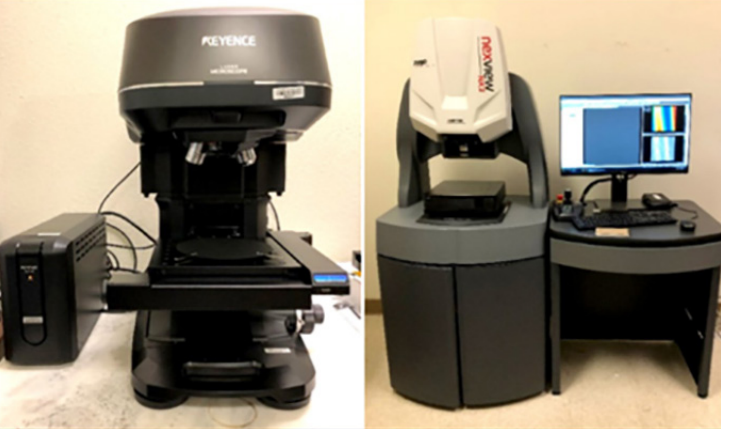
problems, we are living with higher adiabat, and it’s working out okay,” Hurricane said. “But we would like to go to a lower adiabat eventually, and diamond (unlike CH, with its amorphous structure) does have a floor on how low of an adiabat we can go to, because we need that strong first shock. Each of these ablators has its own pros and cons, and we were just trying to find any combination that works.”

Hoping to find alternatives to diamond that could enable a lower adiabat, researchers are now studying amorphous ablator materials with good density, such as diamond-like high-density carbon, boron, and boron carbide. Experiments also are underway to assess the potential of alternative hohlraum designs, such as the I-Raum and Frustraum, that show promise of coupling additional energy to the target capsule.

—Charlie Osolin



(Left) Target Fabrication S&T team members Tom Braun and Chantel Aracne-Ruddle with a PACVD diamond coater developed by Diamond Materials. (Right) The purple glow of the plasma is visible in the viewing port of the polishing chamber. The shells are lapped and polished to achieve the desired ablator thickness and surface quality.



Two new metrology instruments, the Keyence VK-X1000 (left) and the Zygo NexView NX2 (right), were installed in the Target Fabrication S&T labs in the spring of 2020.



Credit: Jason Laurea

Chapter 5

LASER IMPROVEMENTS CONTRIBUTED TO RECORD FUSION EXPERIMENT

LNL scientists set a high bar with the level of laser energy, accuracy, and consistency they expected for the record-setting experiment that brought researchers to the threshold of ignition. Thanks to the work of innovative NIF & Photon Science laser system engineering, operations, and optic materials teams, NIF was more than up to the challenge.

NIF’s lasers delivered slightly more than the requested 1.9 megajoules (MJ) of laser energy at 440 terawatts (TW) of peak power for the shot that produced a historic 1.35 megajoules (million joules) of fusion energy. The 192 beams hit precisely on target with the quality, shape, and exacting trillionths-of-a-second timing required.

The shot’s success didn’t happen overnight. Multi-pronged collaborations among the responsible teams have continued since the world’s largest and highest-energy laser was built, said Steven Yang, leader of the BeamLine Integrated Performance (BLIP) group and co-leader of the Laser & Alignment System Engineering (LASE) group.

Those efforts included a recent modernization of the Master Oscillator Room (MOR), where the initial laser pulse is born, a new computer modeling program that provides better control over the behavior of the beams, and improved technology for mitigating damage to laser optics.

“It’s all due to the work that we collectively did, including hardening the optics and deploying better laser technology,” Yang said. “Since the commissioning of the NIF laser, we have been working continuously on increasing the energy and power delivered to the target. It has been a long march to this type of level.”

Jean-Michel Di Nicola, NIF’s Laser Systems Engineering leader, said the work reaching the threshold of ignition was built on “the shoulders of giants.”

That includes the teams of people who designed NIF and its computational models and diagnostics, and “everybody else who contributed to get the laser performance where it is today, not just a few of us over the last year,” he said. “We’re constantly interacting, pushing the boundaries from all sides.”

Amplifying a single low-energy laser pulse from the MOR into 192 high-energy beams that are focused into a pencil-eraser-sized target, the hohlraum, inside the Target Chamber is no small task. Along the journey, which encompasses about 1,500 meters in just five microseconds, the beams pass through about 7,500 meter-sized optics and 26,000 smaller ones that make NIF the world’s largest optical instrument.

“It’s quite amazing we can accomplish this pulse shape with this level of accuracy for such a short pulse.”

Laser Systems Engineering Leader
Jean-Michel Di Nicola

LLNL scientists have previously compared the act of aiming those beams to a pitcher throwing a baseball from the pitcher’s mound at San Francisco’s Oracle Park into the strike zone at home plate at Dodger Stadium in Los Angeles, 350 miles south. To stretch the analogy further, the campaign of hybrid experiments that culminated in the record-setting shot would require the pitcher to throw the ball on a predetermined trajectory while compensating for any known obstacles, and then adjusting the ball’s speed as it zips through the strike zone and settles into the catcher’s mitt.

For the Aug. 8 shot, the strike zone became smaller because researchers reduced the two hohlraum laser entrance hole (LEH) apertures to just 3.1 millimeters to confine more x-ray energy around the target capsule. This allowed scientists to extend the duration of the



NIF laser pulses are born in the Master Oscillator Room, in which a compact laser oscillator generates low-energy (a few nanojoules) laser pulses. Credit: Jason Laurea

laser pulse by a few hundred picoseconds (trillionths of a second) once it entered the LEHs.

In an inertial confinement fusion (ICF) experiment, the lasers heat the hohlraum, resulting in x rays that ablate the surface of a peppercorn-sized target capsule suspended in the hohlraum, triggering an implosion that compresses and heats the deuterium-tritium (DT) fuel mix inside until the hydrogen atoms fuse, releasing neutrons and other forms of energy.

Extending the pulse time shortened the coast time between when the laser shut down and the moment the imploded target capsule stagnated at maximum compression.

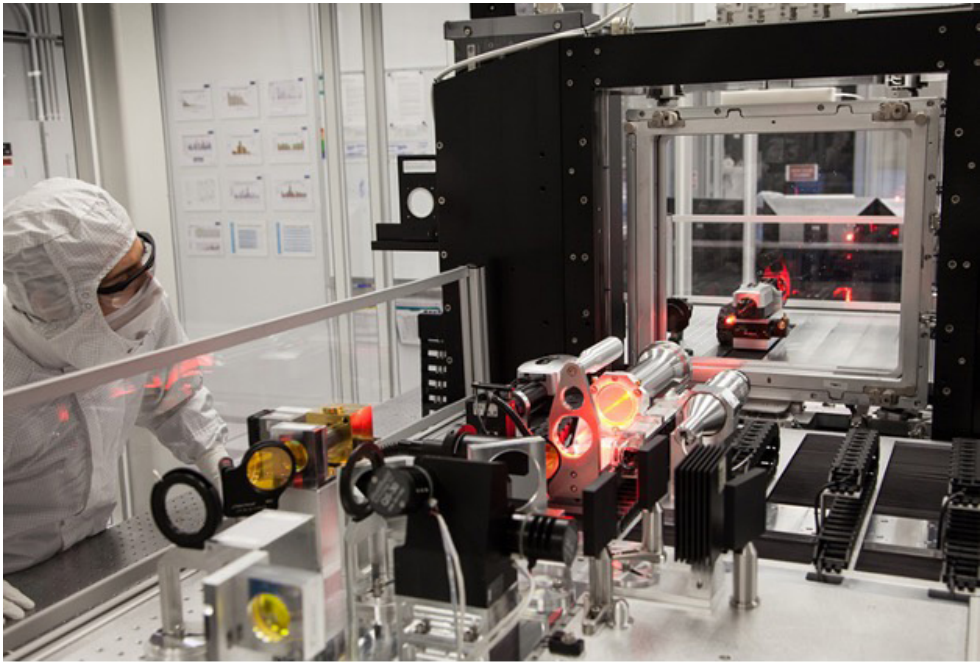
“A key way to make the implosion low-coast, which greatly increases the pressure and temperature in the fusion fuel, is to keep the hohlraum hot by leaving the laser on late,” said ICF Chief Scientist Omar Hurricane.

Researchers have previously known that tweaking the wavelengths of certain beams would control the exchange of energy between the beams that cross each other—an effect known as cross-beam energy transfer (CBET)—as they entered the LEH. Starting with the Hybrid-E campaign in 2019, using larger capsules and low gas fill, controlling CBET became another lever to reduce implosion asymmetries that detrimentally limited the compression, pressure, and confinement time of the DT fuel.

But preparing the beams to arrive properly at the end of the journey starts at the beginning. “You wouldn’t be able to recognize the pulse that we have to inject at the beginning of the laser to match the (scientists’) request at the Target Chamber Center,” Di Nicola said.

About two years ago, a team of top LLNL laser experts embarked on designing, testing, and deploying a new MOR architecture, from the oscillator to the pulse-shaping system input. The modernization included taking advantage of new fiber-optic technology not available when the original MOR was built 20 years ago.

The upgrades have improved the shot-to-shot consistency of the laser’s performance by about three times, a key for fine-tuning laser power balance and accuracy and



Optics Mitigation Facility operator Constantine Karkazis inspects CO₂ laser processing hardware. The NIF fused silica optic is mounted within a large translation stage (the large black vertical structure). Inspection microscopes and laser delivery optics are in the foreground. Credit: Jason Laurea

providing more flexibility to turn CBET from a liability to an advantage. That consistency aided physicists when designing and modeling experiments.

The laser improvements “did remove a

“This is a very, very exciting time.”

Optics and Materials Science & Technology Program Director
Tayyab Suratwala

lot of uncertainty about what we were doing, reduced the complexity of all the things we had to worry about,” Hurricane said. “Those fixes did seem to correlate with our great progress on the physics side.”

The team was recently honored with a National Nuclear Security Administration (NNSA) “Defense Programs Award of

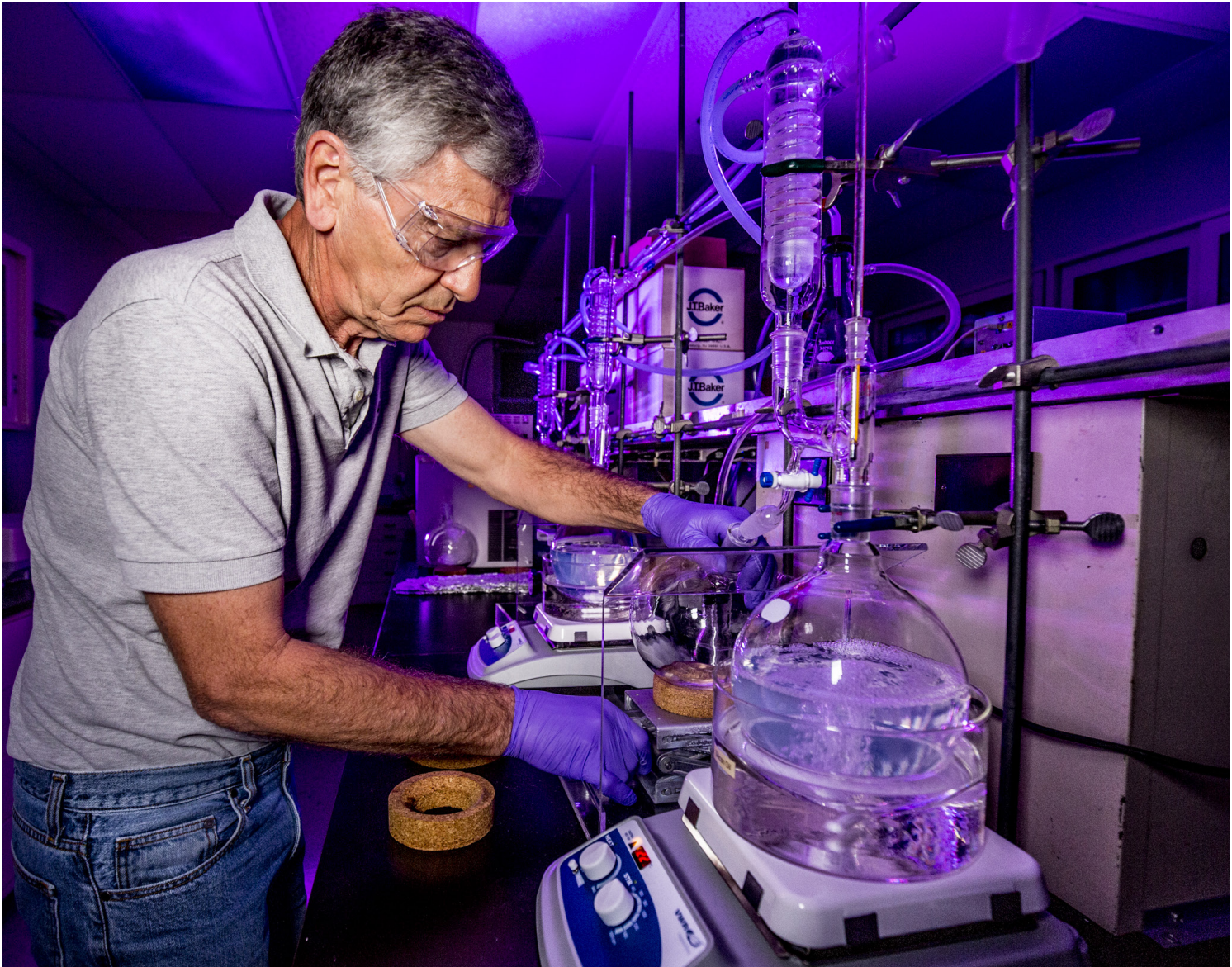
Excellence” for its work on the “design and implementation of the novel master oscillator system for improved control of stewardship experiments on NIF.”

“It was one of the highlights of my 12-year career at LLNL to lead such an outstanding team that delivered a major upgrade for NIF,” Di Nicola said.

“The laser ended up delivering more energy than requested, which was a really nice surprise,” added LLNL physicist Annie Kritcher, lead designer for the Hybrid-E experiment. “They’ve gotten a lot better in delivering high energy and precise laser pulse shaping.”

The laser pulses are generated in the MOR and injected into a complex system of laser amplifier glass, flashlamps, and related components. The system—spread over two laser bays, switchyards, and final optics assemblies in the target bay—splits, amplifies, and focuses the beams.

The laser amplification process damages optics. So optical materials experts have



LLNL Chemist Paul Ehrmann prepares an anti-reflective coating used on NIF optics to overcome energy-robbing reflections and limit damage from the rear surface of the facility's grating debris shields. Credit: Mark Meamber

devised technologies and techniques to protect the optics or mitigate the damage. These measures have allowed NIF to operate at a routinely sustainable energy level of 1.9 MJ and, once, as high as 2.15 MJ in a laser test; both exceed the original design specification of 1.8 MJ. The team is working toward giving experimenters a greater than 2 MJ capability by late next year.

“There has been this series of very important technologies that have helped enable these optics to be survivable so that NIF can operate the way it does today,” said Tayyab Suratwala, program director for Optics and Materials Science & Technology.

Suratwala credits the development of techniques that enabled fabrication of NIF's fused silica optics to minimized damage

caused by imperfections on their surfaces. NIF also developed the advanced mitigation process (AMP), a patented chemical method that makes surfaces more damage resistant by removing impurities and absorbing microfractures.

Suratwala cited the recent development of three technologies to manage the

damage-inducing debris and shrapnel generated by the high-velocity shots:

- Antireflective (AR) coating on the fused silica grating debris shields (GDSs), the penultimate optic placed before the laser beams enter the Target Chamber.
- Fused silica debris shields that protect the valuable GDSs from debris from low-cost disposable debris shields (DDSs).
- Incorporation of debris-blocking metal shields that are being designed and installed in the final optics assembly (FOA), where the laser light is doubled in frequency to a visible green light (2ω) and then to ultraviolet (3ω).

“The progression of that set of technologies is allowing NIF to do both more shots as well as doing higher power and energy shots,” Suratwala said.

The laser and optics teams work closely to take full advantage of these improvements.

“We talk to each other a few times a week, both in terms of the day-to-day behavior of the laser system as well as for developing new capabilities,” Suratwala said. “That requires a very strong partnership of not just the laser systems engineering group, like Jean-Michel Di Nicola and Stephen Yang, but also the operations folks, people like Stanley Sommer and Tom Kohut and their teams.”

In addition, the installation of a code called the Virtual Beam Line++ (VBL++) in 2019 provided a powerful new tool to use on the Laboratory's high-performance computing platform to simulate how the laser performs.

“After we shape the pulse, we have to model the distortions and characterize them,” Di Nicola said. “That's a thing that few people realize that we have to do. That's what the virtual beam line is for. It does all the diffractions, amplifications, nonlinear optics, behavior of the light. We want to know what to inject to get the pulse that the experimentalist wants at the end of the laser.

“It's quite amazing we can accomplish this pulse shape with this level of accuracy for such a short pulse,” he said.

This year, NIF completed recommissioning the Precision Diagnostic System (PDS), which has an array of scientific measurement tools to help test ways to



Anthony Oceguera installs and aligns a calibration calorimeter inside the NIF Precision Diagnostic System target diagnostics chamber. Credit: Abe Handler

increase laser performance without risking the main system.

Yang noted that the addition of a new calorimeter inside the Target Chamber provides another tool to ensure the laser is performing as designed.

“It doesn't impact laser delivery per se, but it does give us confidence that what we're reporting now is the actual number,” Yang said. “When we say 1.92 megajoules, we

know with a very small uncertainty that is the number.”

Suratwala started his career at the Lab just as construction began on NIF, so he's heartened by all the advancements that have brought scientists to the edge of ignition.

“I've seen it go from dirt to what it is today,” he said. “This is a very, very exciting time.”

—Benny Evangelista



Credit: Randy Wong

Chapter 6

MODELS & SIMULATIONS HELP MAP NIF'S PATH TO IGNITION

You wouldn't set out on a cross-country road trip without a current map or a functioning GPS. You might eventually reach your destination, but you might take a lot of wrong turns before you got there. Likewise, inertial confinement fusion (ICF) researchers don't design and carry out experiments on NIF without the guidance of increasingly sophisticated computational models and simulations informed by diagnostic data and analysis of previous experiments. Simulations allow the researchers to design implosion platforms and conduct trial-and-error tests of their theories before trying them out in time-consuming and costly experiments. Computationally intensive 3D models, 2D integrated simulations that model cross-beam-energy transfer (CBET) inline, large computational ensembles, and simplified mathematical and data-based models played important roles over the decade of research building to the record-setting Aug. 8, 2021, experiment that produced 1.35 megajoules of fusion energy. The precision required for simulating these experiments, coupled with Lawrence Livermore National Laboratory's world-class high-performance computing resources, can also improve the fidelity of simulations of interest to the National Nuclear Security Administration (NNSA)'s Stockpile Stewardship Program. Nuclear weapon scientists and engineers use sophisticated simulations informed by NIF experimental results to assess the performance of nuclear weapon systems and perform weapon science and engineering calculations. NIF experimental data and simulations are combined with deep learning methods to improve understanding of the elements of ICF as well as the effects of aging on nuclear weapons in lieu of underground testing. NIF fires 192 high-energy lasers into a fusion target the size of a pencil eraser and is capable of producing temperatures of more than



Data from experiments on NIF (right) help inform and validate simulations carried out on LLNL’s high-performance computing capabilities such as the Sierra supercomputer (left), a 125-petaFLOPs (quadrillion operations per second) machine that is one of the fastest in the world. Credit: Tanya Quijalvo

100 million degrees Kelvin and pressures of hundreds of billions of Earth atmospheres.

NIF’s progress toward ignition—formally defined as when the energy produced by fusion reactions meets or exceeds the laser energy delivered to the target—was largely driven by improvements in the design of experiments fielded on NIF that were shaped by the results of previous shots and by enhanced experiment-based modeling and simulation.

Computer codes were used to design, optimize, construct, and field the experiments while continually advancing understanding of key multi-physics mechanisms.

The hybrid experiments have increased the scale of the implosion to couple more energy

“You make a relatively small change in the inputs and suddenly you see this jump—that’s the threshold, or cliff-like, behavior we’ve been talking about for years. That’s one of the indications that ignition is about to happen”

ICF Chief Scientist Omar Hurricane

to the hot spot, as compared to previous high-yield baseline designs, and to achieve high levels of hot-spot pressure—moving NIF closer to ignition at the same level of laser

energy and power. The record-breaking shot also benefited from a high-quality diamond target capsule and other aspects of new target design.

“We had to improve the efficiency of the hohlraum and balance many other design parameters at the same time to achieve the high pressures,” said LLNL physicist Annie Kritcher, lead designer for the experiment that brought NIF to the threshold of ignition.

“Doing this in an integrated design sense, where we considered the detailed capsule physics together with what we could achieve with the hohlraum, was a key aspect” of the experiment’s success,

Kritcher said. “We rely on the models for a lot of things: shock timing, energetics, symmetry during most of the (laser) pulse, implosion velocity, and so forth.”

While “modeling these extreme plasma conditions is very difficult,” she added, “they do extremely well in calculating the early-time radiation drive symmetry for these experiments, thanks to the development of the inline CBET modeling capability.

“These experiments will continue to improve our modeling capability,” she said.

Simulations are also used to infer certain properties of NIF experiments that can’t be measured directly, such as the extent of alpha heating in the cold fuel surrounding the hot spot, referred to as yield amplification, or Y_{amp} . In the Aug. 8 experiment, energy yield was

amplified by about 30 times over what it would have been without alpha heating—about six times more than the best previous Y_{amp} .

“That sudden jump is what we’re looking for,” said ICF Chief Scientist Omar Hurricane. “That’s one of the indications that ignition is about to happen. You make a relatively small change in the inputs and suddenly you see this jump—that’s the threshold, or cliff-like, behavior we’ve been talking about for years.

“It’s super exciting because we’re starting to see it’s not a fantasy anymore. It’s actually happening.”

ICF experiments are modelled primarily by LLNL’s HYDRA multi-physics radiation-hydrodynamics code and the legacy LASNEX ICF code, which have been extensively validated against experiments, including hundreds of publications, over several decades.

“Knowing where the models can be trusted and where semi-analytical models were needed to make progress was important in this research.”

Lead Designer Annie Kritcher

HYDRA, with more than one million lines of code, has packages to simulate radiation transfer, atomic physics, hydrodynamics, laser propagation, and a number of other physics effects so that it can handle a broad range of NIF experiments.

“We know the (standard multi-physics) models have difficulty, especially in the late-time beam propagation, and that is crucial for maintaining symmetry and implosion performance,” Kritcher said. “So in that regime, we use data-driven models to guide design choices. Knowing where the models can be trusted and where semi-analytical models were needed to make progress was important in this research.”

A Change in Awareness

The reliability of the models was an important issue in early NIF ignition experiments that produced fusion yields of only a few kilojoules—far less than the models predicted. A 2015 NNSA review of the ignition program found that models and codes predicting that NIF would attain ignition



Key contributors to the NIF modeling and simulation program (from left): Kelli Humbird, Debbie Callahan, Dan Clark, Scott Sepke, Annie Kritcher, Marty Marinak, Denise Hinkel, Chris Young, Omar Hurricane, Ryan Nora, and Tod Woods. Not shown: Chris Weber, Jose Milovich, and Oggie Jones. Credit: James Wickboldt

conditions “are not capturing the necessary physics to make such predictions with confidence.”

The review also said experimental efforts were “frustrated by the inability to distinguish key differences” between laser shots, with similar experimental designs producing inconsistent results.

“The models we were using previously were very optimistic in their predictions,” Hurricane acknowledged. “Knowing where you can trust the model and where you can’t is not really an issue for the model, it’s more about a change in your own awareness. This skill is what we call

designer judgment, which is particularly important for the people who are responsible for nuclear weapons codes.”

In addition, he said, the degradations in implosion performance caused by such factors as the tent that suspends the target capsule in the hohlraum, the tube used to fill the capsule with deuterium-tritium (DT) fuel, and contamination of the fuel by capsule material, “weren’t in the models from years back, either because we didn’t have the computational power to include them, or we didn’t think they mattered, or we just didn’t know they were there.

“Those are the key aspects of higher-fidelity representations of what we are actually doing in the experiments—more capsule detail, more fill-tube detail, more tent detail, more hohlraum detail. We now have much higher-fidelity representations than we had before.”

In particular, advances in computer architecture allowed high-resolution 3D modeling and simulations by Dan Clark, Chris Weber, and their colleagues, opening the door to identifying several key effects causing degradation in implosion performance.

“We’ve spent the last several years evolving our capsule modeling capabilities to include all of the various degradations that we’re aware of that are impacting NIF implosions in a single integrated model,” Clark said. “It’s challenging given the disparate scales at play, from sub-micron to millimeters, and the three-dimensionality of our implosions. That means you need a model that is both high-resolution and three-dimensional, and that’s computationally very demanding.

“We’re not there quite yet,” Clark said, “but we’ve made a lot of progress combining these two requirements—high resolution and 3D—to the point that our simulations are beginning to capture many of the features we see in experiment. And the more data you’re able to match on any given experiment, the more confidence you can have in applying that model to extrapolating and predicting future experiments, which is ultimately what we’re aiming for—a tool that can help guide us from 100 kilojoules to 1 megajoule and ultimately to 10 or 100 megajoules.”

In addition, 3D hohlraum modeling has been invaluable in assessing the impact of non-azimuthally symmetrical target features, increasing researchers’ understanding of the delicate play of the different components of the NIF target, as well as suggesting further improvements.

“There is also an effort afoot to improve the predictive capability of hohlraum modeling,” said Denise Hinkel, team lead for focused hohlraum modeling. “Typically, an integrated hohlraum-capsule simulation overpredicts the radiation drive that implodes the capsule as well as the amount of drive at the hohlraum waist, which impacts implosion symmetry,” she said. “Hypothesis-driven, focused experiments are underway at NIF to enhance both scientific understanding and predictive capability for hohlraum modeling.”

Keeping It Simple

Some issues, such as the multiple sources of asymmetries that degrade implosion performance, are so complex that comprehensive simulations become difficult to analyze. When that happens, researchers

have found ways to simplify aspects of the implosion to reveal hidden relationships.

An example is the piston model, a mathematical abstraction of an implosion developed by Hurricane, Dan Casey, and their colleagues.

“The ICF implosion is a very complicated thing, and that’s why we rely on computer simulations so heavily,” Hurricane said. “But for the particular problem of asymmetry, you can abstract an implosion to a simple arrangement of pistons that looks a lot like a piston-driven rotary engine that you see in old biplanes from the 1920s.

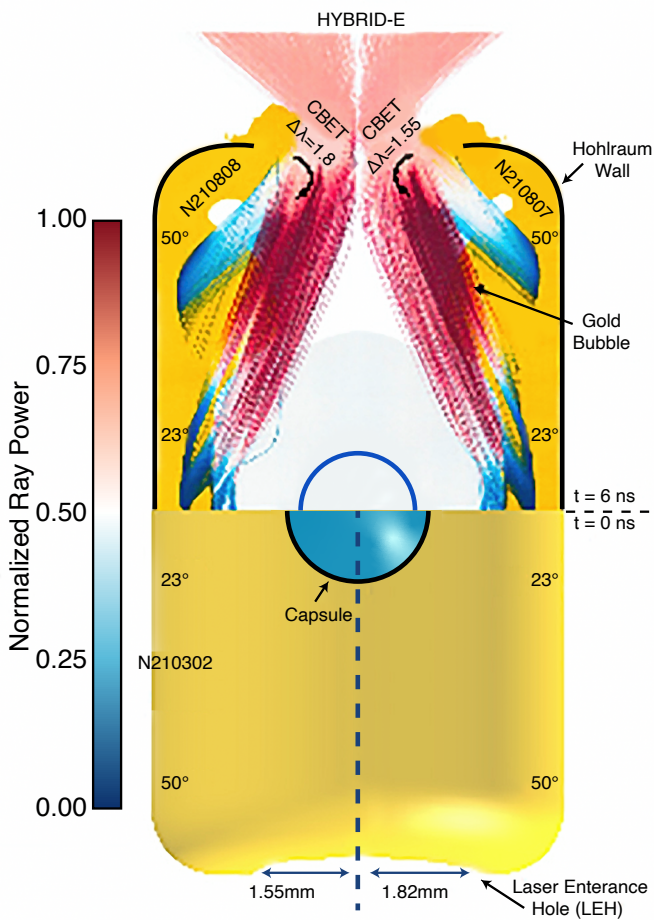
“You can make a mathematical model that’s actually tractable—you can solve the math, and you see a number of simple but deep relationships between things we can measure and see in the experiments that were not obvious before.

“It’s an enormous simplification of a very complicated system that in this case was actually very, very productive and useful,” Hurricane said. “You get excited when you can explain some really complicated systems with a handful of simple equations.”

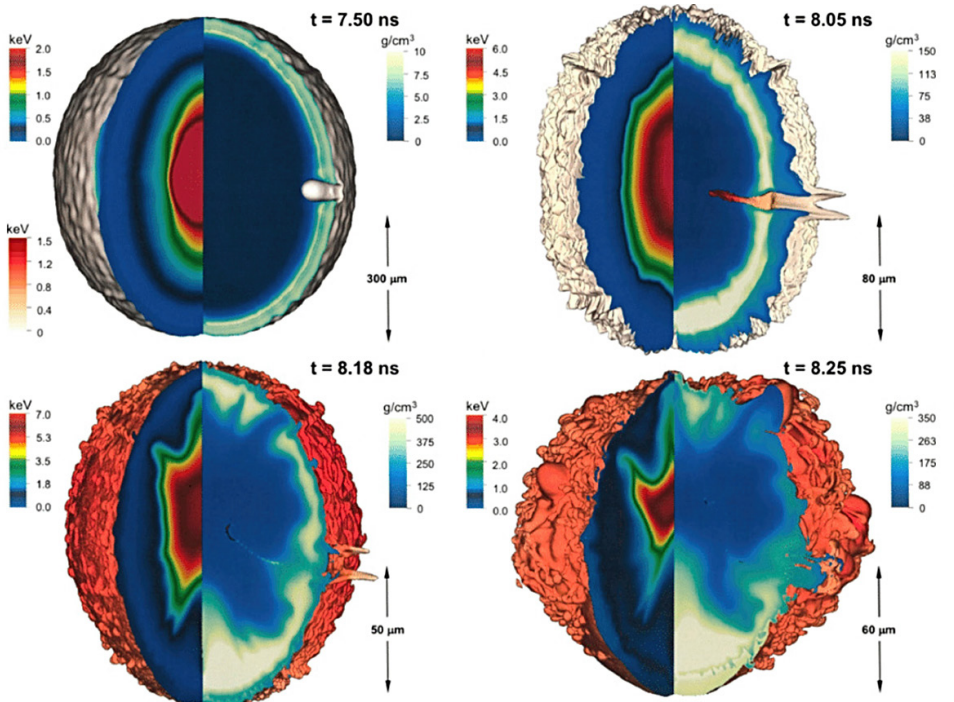
Simplification was also the goal of a data-based model for the late-time hohlraum radiation drive at the waist of the hohlraum that impacts symmetry. It was developed by LLNL physicist Debbie Callahan, a co-founder of the hybrid series of experiments. Simple models can be used to quickly scope out design parameter space under different assumptions and then identify interesting parts of that space for further study using more sophisticated tools.

“A key aspect of the hybrid strategy is to use some empirical models to guide us through the huge design space,” Kritcher said. “Being able to narrow down to something that looks like it’s going to meet all the criteria in just a handful of shots is very difficult. So, we have the famous ‘Debbie curve’ for hohlraum designers to figure out how to balance all the hohlraum parameters against what you’re trying to achieve for the capsule implosion.”

Large computational ensembles are another way to look for patterns in simulated data. An ensemble, used in machine learning for such things as weather forecasting, is a suite of sometimes thousands of simulations



HYDRA simulations with inline cross-beam-energy-transfer of a Hybrid-E experiment on March 7, 2021, (top right) and the Aug. 8, 2021 shot (top left), which model the laser beam propagation through the plasma-filled hohlraum to achieve precise control of radiation symmetry. (Bottom) The initial target conditions show the design changes to the target compared to previous Hybrid-E experiments. Credit: Andrea Kritcher



A 3D full-sphere simulation of a June 2017 NIF shot close to bang time (the moment of peak neutron emission). In each snapshot, the left half of the cutaway shows ion temperature, the right half shows mass density, and the outer surface is the ablation front colored by the electron temperature. The perturbation caused by the fill tube can be seen penetrating the shell and hot spot in the top images before being deflected upwards by the up-down drive asymmetry. This asymmetry causes the mass accumulation visible in the lower hemisphere and thinning in the upper hemisphere, and ultimately leads to the rupture of the confining shell seen in the last snapshot. Credit: Dan Clark

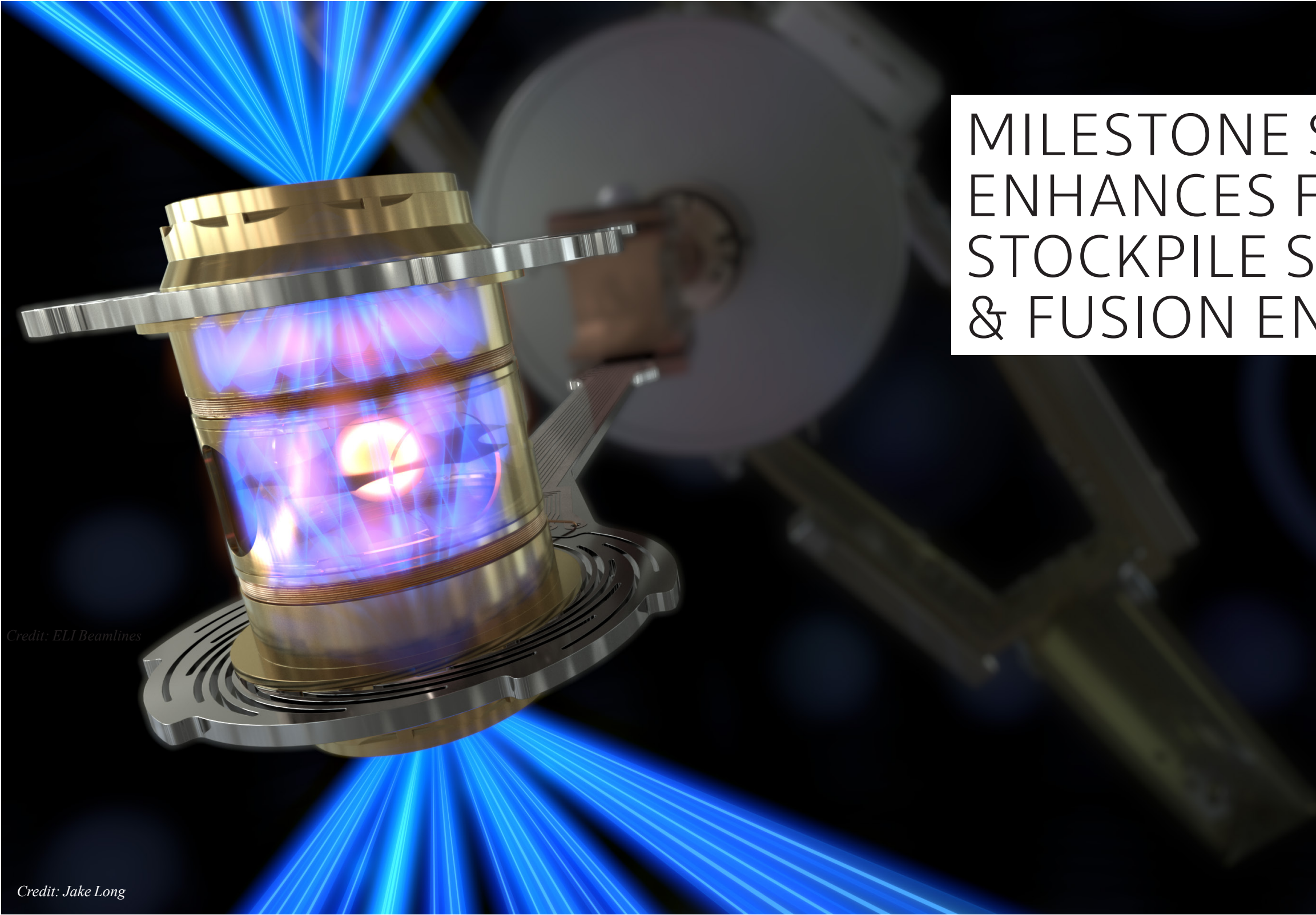
in which the variables are slightly changed over time to create a large database of inputs and outputs. Ensembles are used to develop quantitative, detailed estimates of the relative impact of physics phenomena and degradation mechanisms in ICF experiments.

Researchers are also building improved predictive models that can be used to foresee and design new NIF experiments. These models combine simulation prediction with the totality of existing NIF implosion data to give more accurate results.

“There’s this complicated back and forth between diagnostics—a physical picture of what the implosion should be doing—and our models,” Hurricane said. “It’s an involved, iterative process. It takes time to understand what you’re doing and what you’re seeing.

“It’s a process of learning,” he said, “because you can’t always anticipate all the problems. Sometimes your guesses at what the problems will be are wrong—Mother Nature tells you different. Usually, she finds more problems for you than what you thought of on your own.”

—Charlie Osolin



Credit: ELI Beamlines

Credit: Jake Long

Chapter 7

MILESTONE SHOT ENHANCES FUTURE OF STOCKPILE STEWARDSHIP & FUSION ENERGY SCIENCE

When NIF fired a laser shot on Aug. 8, 2021, that came close to achieving nuclear fusion ignition through inertial confinement fusion (ICF), the scientific world immediately took notice. Two of the fields that stand to gain from NIF’s record shot are stockpile stewardship science and the quest for inertial fusion energy (IFE).

The National Nuclear Security Administration (NNSA)’s science-based Stockpile Stewardship Program (SSP) funds Lawrence Livermore National Laboratory’s work to maintain the safety, security, and reliability of the nation’s nuclear deterrent—the Laboratory’s primary mission. NIF plays a significant role in SSP research. Accessing the energies of fusion ignition will enable stockpile stewardship experiments at a new level of high energy density (HED) conditions.

Meanwhile, fusion researchers around the world are working to develop the technology to generate electricity through fusion. Achieving ignition could lay the groundwork for developing an IFE-based power plant that could someday provide a safe, carbon-free, limitless, and sustainable source of electricity.

Both fusion and SSP researchers benefited from “the shot” heard around the scientific community because both controlled and uncontrolled fusion take place at the same HED conditions—pressures of hundreds of billions of Earth atmospheres and temperatures in the hundreds of millions of degrees, hotter than the core of the sun.

“There are many really cool pieces of data from this experiment,” said Mark Herrmann, program director for the Weapon Physics and Design Program in LLNL’s Weapons and Complex Integration Directorate. “It’s really a testament to this Lab and the ability to move the needle on hard S&T things,” he said, “and the commitment to understand the very important processes that go on in our nuclear weapons, and to our partnerships with many external partners—General Atomics, Los

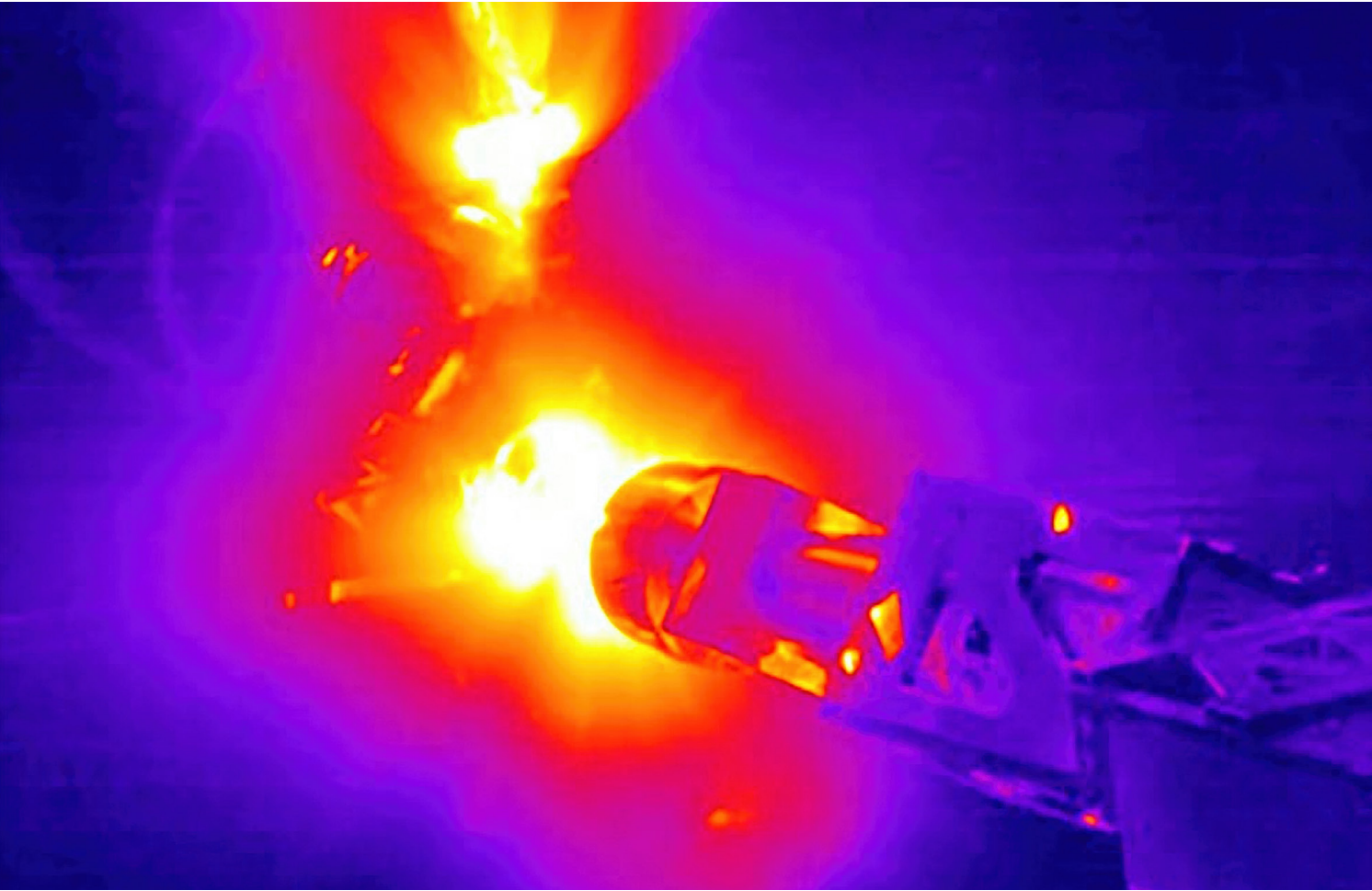


Image of a NIF experiment at the moment of peak implosion. This experiment was aimed at developing a high-pressure strength measurement capability for plutonium.

Alamos and Sandia national laboratories, the University of Rochester, and many others.”

It was “definitely a game-changer in terms of our capabilities,” Herrmann said. “It vastly expands the landscape of what we can aspire to and really increases our impact on stewardship.”

After years of experiments that produced energies in the kilojoule range, the fuel in the peppercorn-sized capsule of the Aug. 8, 2021, shot yielded 1.35 megajoules (MJ), eight times more energy than the previous record shot and about 70 percent of the 1.92 MJ fired by NIF’s 192 lasers.

Ignition through ICF is defined to take place, according to the National Academy of

Science and NNSA, when a NIF implosion yields as much or more fusion energy than the amount of laser energy delivered to the target.

For the Stockpile Stewardship Program, the record shot provides access to a new regime of high energy density plasmas to test and verify the Laboratory’s nuclear weapons-related simulation codes. NIF performs experimental studies of fusion ignition and its subsequent thermonuclear burn, which provide the immense energy of modern nuclear weapons.

NIF’s capabilities are essential for stockpile stewardship. When the United States ended the testing of nuclear devices in the 1990s, the nuclear security enterprise moved to

a new model of assuring the stockpile’s readiness. Stockpile stewardship uses high-performance computing and simulation to model the physics of weapons systems during and after detonation, combined with hydrodynamic tests on NIF and other facilities that explore the behavior of materials under extreme conditions of temperature and pressure.

Subcritical tests, which subject small samples of plutonium to these conditions in amounts so low that the samples are incapable of going critical, have also been crucial to stockpile stewardship research in recent years. NIF has over time achieved higher and higher fusion yields, providing better data to improve the computer models. But without the ability

to experiment and gather data in the exact conditions where fusion ignition takes place, the fidelity of nuclear weapon simulations is not as certain as researchers would like.

“Fundamentally, nuclear weapons operate in high energy density conditions,” Herrmann explained. “Matter behaves differently at high temperatures and pressures. Understanding this behavior is fundamental to our understanding of how nuclear weapons work.”

“When we stopped testing more than 30 years ago, we lost experimental access to the HED regime,” he said. “We needed to reconstitute our access to this regime through the experiments we perform at NIF.”

Several needs of the SSP are laid out in a National Academies of Sciences, Engineering, and Medicine (NASEM) report, *Plasma Science: Enabling Technology, Sustainability, Security, and Exploration*, released in May 2020. Stockpile stewardship requires enhanced capabilities to recreate more weapon-like conditions in experimental facilities, the report noted.

Each year, the three national nuclear security laboratories—LLNL, Los Alamos, and Sandia—perform an assessment for the president certifying the readiness of the stockpile. These assessments require focused experiments such as characterizing materials used in the nuclear stockpile at HED conditions.

Those conditions are also necessary to understand the impacts on nuclear device performance of aging components in the stockpile, according to the report.

As new materials and processes are applied to renew weapon systems in the stockpile through life-extension and modification programs, these materials and processes must be tested under HED conditions. Finally, evaluating the HED plasma environment requires innovative, sophisticated diagnostics capable of accurate measurements under burning plasma conditions.

NIF’s technological innovations include many such advanced diagnostics (instruments that measure experimental results), and data from these instruments helped researchers



NIF experiments are uniquely capable of informing and validating three-dimensional weapons-simulation computer codes that support the W80-4 warhead Life Extension Program (LEP) effort.

achieve the near-ignition conditions of the Aug. 8 shot. At ICF temperatures and energy densities, it will now be possible to access the conditions needed to validate stockpile stew-

better understand how the weapons operate,” Herrmann said. “But another reason the shot is important is that this fusing plasma released a lot of energy in a very short time, generating

far higher peak powers than NIF’s lasers can generate. That higher power output from fusion will let us access phenomena experimentally that we don’t have access to today.”

The record shot has also helped fuel new discussions about the possibility of harnessing fusion to generate energy for the electric grid. Federal funding of IFE has

been low to nonexistent in recent years.

“This result places NIF on the threshold of fusion ignition for the first time ever,” said Tammy Ma, the NIF&PS program element leader for High-Intensity Laser High Energy

“Matter behaves differently at high temperatures and pressures. Understanding this behavior is fundamental to our understanding of how nuclear weapons work.”

Program Director Mark Herrmann, Weapons and Complex Integration Physics and Design Program

ardship simulation codes to higher fidelity at weapons-relevant conditions through experiments at NIF.

“All modern nuclear weapons rely on nuclear fusion and so we study fusion to

Density Science. “And it demonstrates the feasibility of laboratory-scale laser-driven inertial confinement fusion to achieve high-yield conditions.”

Building on support within the R&D community for a renewed push on IFE, Livermore is working to coordinate with the U.S. Department of Energy (DOE) national labs, their academic partners in HED physics research, and the private sector to shape a proposal for IFE research.

A workshop on IFE led by Livermore’s Alex Zylstra was held in mid-November 2021 to bring the community together, and another followed in February 2022. The White House held a Fusion Energy Summit on March 17, and Ma co-chaired a DOE workshop in June to plan an IFE research portfolio.

Although the August shot helped ignite a fire in the fusion community, many steps lie ahead. The first, according to Ma, is achieving ignition. Next is demonstrating high gain: although energy gain of, for example, one percent over input energy qualifies as ignition under the NAS/NNSA definition, a working power plant would need a much higher return on energy—perhaps 100 times as much.

The research would also have to demonstrate the repeatability of this energy output, shot after shot, with shots occurring 10 times a second or more. Finally, as the research community turns to IFE power-plant design, the economics of producing electricity must be demonstrated to be favorable.

“Economics is the name of the game in IFE,” Ma said. “We will need more efficient lasers, cost-effective production of the fuel pellets, streamlined heat extraction and energy conversion, and other improvements.”

While the Aug. 8 NIF shot fell just short of ignition, Ma believes that now is the time to move forward with IFE research: “There’s lots of new advancements to justify it,” she

said—“high-repetition-rate lasers, artificial intelligence to help with data analysis, new physics diagnostics, advanced materials.

“Even though we haven’t achieved ignition, we’ve been making good progress toward it, and inertial fusion energy is such a big grand challenge that you can’t wait to achieve ignition to start on the development of the other needed technologies—otherwise you’re already behind.”

An electricity-producing IFE power plant would require such technologies as a driver and target injection and tracking system, all operating at high repetition rates. It would also need an energy conversion system to produce electricity from heat, robust first walls around the fusion source, and blankets made of robust mate-

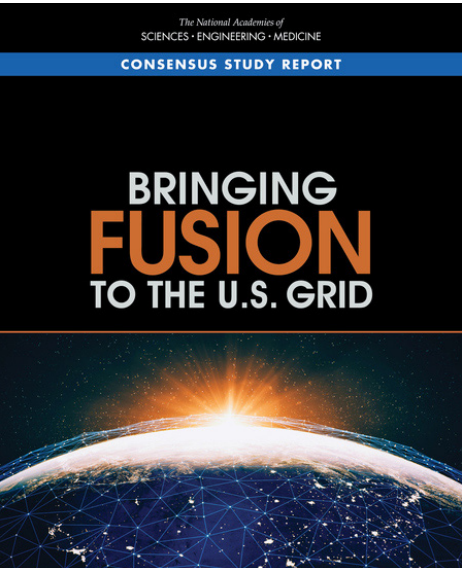
rials to protect the walls from high temperatures.

Other elements of a working fusion power system would include technologies for tritium breeding, processing, and recovery, remote maintenance systems, and more.

NIF will play a significant role in any such research program. Although it is not designed to generate electricity—it is a research tool—NIF is currently the only place in the world where integrated experiments at the megajoule level are possible. The facility is where researchers can test the robustness of designs, the target-driver sensitivities that govern which shots achieve fusion burn, and the factors that cause them to fall short, such as asymmetries and target imperfections.

The fusion field has collectively received a psychological upsurge from the milestone shot, including a budding private-sector fusion start-up community funded by venture capital.

“The NIF result does not invalidate other fusion technologies—in fact, it provides a potential boost to them,” Ma explained. “This shot demonstrates that our high energy density simulation codes were not all that far off. The



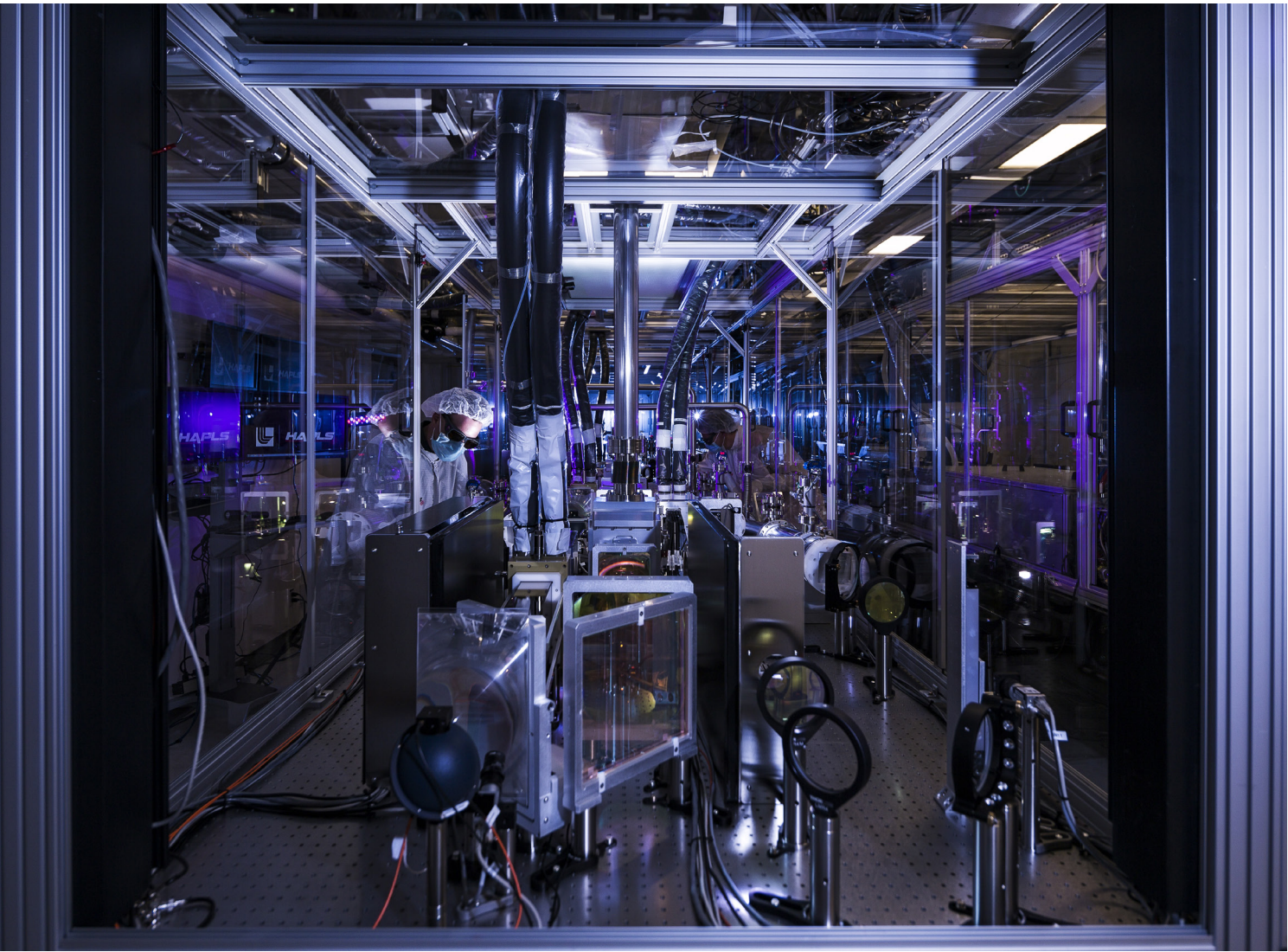
Recent reports by the national academies and an influential DOE advisory committee have recommended stepped-up U.S. investment in fusion energy. The success of NIF’s shot has bolstered the view within the fusion R&D community that achieving ignition through inertial confinement is now very close, making the possibility of harnessing fusion to generate electricity much more real.

same fundamental set of simulations proves that our approach is in the right ballpark.”

Private-sector startups are investigating other strategies for igniting fusion, such as compact tokamaks to achieve magnetic confinement fusion. “It’s important for the vitality of a field like fusion to have the private sector involved,” Ma said. “They have a different way of looking at things. They’re focused on a smaller scale and can potentially accept more development risk.”

The NASEM plasma science report called out an important “soft” benefit of reaching the realm of ignition under controlled experimental conditions: it helps promote academic alliances to recruit and train new generations of scientists.

The investments supported by NNSA and DOE’s Office of Science have made the United States the world leader in HED science, giving the nation a competitive advantage.



The LLNL-developed L3-HAPLS (High Rep-Rate Advanced Petawatt Laser System) at the ELI Beamlines Research Center in the Czech Republic is capable of firing at a repetition rate of 10 Hz (10 shots per second). Credit: Damien Jemison

When it was completed in 2009, NIF operated with 60 times more energy than the next biggest laser in the world, the Omega Laser Facility, also in the United States. Now, nearly a decade later, NIF operates with 10 to 20 times the energy of the next most energetic laser, which is in China.

“This world leadership,” Ma said, “along with the compelling scientific opportunities—especially the grand challenge of inertial confinement fusion ignition and the potential

of a path to inertial fusion energy—has been a magnet for the best and brightest scientists and engineers to pursue research in HED science and to work as part of the SSP.”

Ma also pointed out mutually beneficial synergies between IFE and the needs of stockpile stewardship. Advanced targets that could yield high gain for IFE could produce high neutron yield for stewardship applications. Improvements in driver cost and repetition

rate for IFE could similarly mean more high energy density experiments for SSP.

“We can now do two things that we could not before,” Herrmann noted. “We can refine our simulations of the fusion ignition process to better match what really happens during fusion. We can now also use the energy output from these fusion experiments to study and understand new phenomena—at energies that we couldn’t reach before.”

—Allan Chen

National Ignition Facility
Lawrence Livermore National Laboratory
P.O. Box 808, L-664
Livermore, California 94551

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